BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING

FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF MANUFACTURING TECHNOLOGY

ÚSTAV STROJÍRENSKÉ TECHNOLOGIE

OPTIMISATION OF MACHINING PROCESS FOR AN INDUSTRIAL APPLICATION AND A CNC MACHINING CENTRE

OPTIMALIZACE OBRÁBĚCÍHO PROCESU S PRŮMYSLOVOU APLIKACÍ NA OBRÁBĚCÍM CENTRU

MASTER'S THESIS

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ FAKULTA STROJNÍHO INŽENÝRSTVÍ

Zadání diplomové práce

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

Optimalizace obráběcího procesu s průmyslovou aplikací na obráběcím centru

Stručná charakteristika problematiky úkolu:

Implementace automatických systémů do obráběcího centra umožňuje zvýšit produktivitu a snižuje objem manuální práce operátora. Robot může vkládat obrobky a odebírat obrobené součásti, není tedy nutná fyzická práce člověka. CNC obráběcí centra mohou pracovat pod minimálním dohledem, jsou–li vhodně monitorovaná a automatizovaná. Zavedení automatických systému do obráběcího centra je zejména vhodné při velkých sériích obrobků. Před automatizováním procesu obrábění je však potřeba definovat vhodnou technologii obrábění, nástroje a optimalizovat řezné podmínky.

Cíle diplomové práce:

Analýza současného stavu technologie.
Návrh zlepšení dosavadního obráběcího procesu.
Optimalizace řezných podmínek a nástrojů pro umožnění automatizace obráběcího procesu.
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Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2019/20

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ABSTRAKT

Tato diplomová práce byla vypracována v průmyslovém kontextu, během stáže ve firmě Metso. Zlepšení obráběcího procesu zajišťovacích šroubů bylo cílem této práce, aby byla umožněna budoucí automatizace zakládání obrobku do stroje. Zlepšení bylo zhodnoceno na základě úrovně autonomie během obrábění, eliminace neprogramovaných zastavení stroje operátorem a dostačujícího odvodu třísek. Implementace automatických systému do číslicově řízeného obráběcího centra umožňuje zvýšení produktivity. Před automatizováním obráběcího procesu však musí být proces optimalizován. Zejména dostatečná fragmentace třísek a jejich evakuace jsou klíčové. Dlouhé nedělené třísky můžou poškodit systémy jako například automatický měnič nástrojů, dopravník třísek nebo průmyslového robota. Dostatečná lámavost třísek může být zaručena správným výběrem technologie a strategie obrábění, výběrem řezného nástroje a řezných podmínek pro daný materiál obrobku.

Klíčová slova

třískové obrábění, CNC obrábění, soustružení, frézování, trochoidní frézování, automatizace, optimalizace, šroub, závity

ABSTRACT

This diploma work was elaborated in industrial context during an internship at the company Metso. Optimising machining process of components called locking bolts was set as a goal to allow future project of workpiece feed automation. Optimising was evaluated by the level of autonomy, elimination of unprogrammed interventions of the machine’s operator and sufficient chip evacuation. Implementation of automatic systems to a CNC machining centre allows increase in productivity. Before automation of machining process, the machining needs to be optimised. Especially good chip fragmentation and evacuation is important. Long unfragmented chips can damage systems the like the automatic tool changer, chip conveyor or industrial robot. Sufficient chip fragmentation is given by choosing a machining technology and strategy, correct cutting tools and correct cutting conditions for given workpiece material.

Key words

machining by cutting, CNC machining, turning, milling, trochoidal milling, automation, optimisation, bolt, threads

ROZŠÍŘENÝ ABSTRAKT

Úvod

Tato diplomová práce byla zpracována během stáže ve společnosti Metso v Mâcon ve Francii, kde se vyrábějí kuželové drtiče Metso. Cílem stáže bylo optimalizovat proces obrábění výroby skupiny komponentů na multifukčním CNC stroji. Zkoumané komponenty byly již mnoho let ve výrobě. Budoucí automatizace obráběcího procesu byla do budoucna zvažována k investici, ale na začátku této stáže nebyla automatizace možná, protože obráběcí proces nebyl optimalizován. Nejdůležitějším kritériem zlepšení byla lámavost a odvod třísek. Dlouhé nefragmentované třísky eliminovaly možnost potenciální automatizace.

Studované komponenty se nazývají zajišťovací šrouby. Jde o šrouby velkých rozměrů a jsou součástmi kuželových drtičů Metso.

Agregáty je třeba rozdrtit na potřebnou velikost. Zmenšení velikosti agregátů se provádí postupně v několika krocích. Kuželový drtič je typ drtiče používaný ke zmenšení velikosti kameniva a obvykle se používá pro sekundární, terciární nebo kvartérní drcení [1].

Šrouby jsou mechanické součásti, které se používají k vytváření závitových spojů. Obvykle lze rozlišit tři části šroubu: hlava šroubu, závit a dřík. Šrouby mohou mít různé velikosti, ale nejpoužívanější a nejznámější jsou šrouby značně malých rozměrů. Například šrouby, které se používají k montáži nábytku, mají průměr jen několik milimetrů a jsou dlouhé jen několik desítek milimetrů. Šrouby malého rozměru se obvykle vyrábějí tvářením kusu drátu za studena a následným závitováním [2].

Šrouby velkého rozměru jsou vyráběny různými technologiemi. V této práci byla zpracována výroba šroubů velkých rozměrů (průměr závitu větší než 100 mm) třískovým obráběním.

Zajišťovací šrouby v Metso v Mâconu byly vyráběny v malých sériích na začátku stáže. Na začátku této stáže byl proces obrábění těchto komponentů neustále pod dohledem operátora. Jako cíl bylo stanoveno zvýšení úrovně automatizace. Díky zvýšení autonomie by během obrábění mohl operátor plnit jiné úkolů, například pracovat paralelně na jiném stroji. Částečná nebo úplná automatizace obráběcího procesu a robotizace byla firmou zvažována jako možná investice. Velikost série bude nejspíš navýšena v důsledku přemístění výroby z jiných výrobních závodů. Díky větší velikosti série by automatizace zlepšila návratnost investic. Proces obrábění však vyžadoval optimalizaci. Zlepšení procesu obrábění bylo hodnoceno dle kritérií autonomie, cílem bylo minimalizovat zásah obsluhy během obrábění. Budoucí automatizace a robotizace jsou možným pokračováním tohoto projektu.

Fragmentace třísky

Parametry, které nejvíce ovlivňují fragmentaci třísek během soustružení, jsou:

- hloubka řezu,
- posuv,
- řezná rychlost,
- řezné kapalina,
- utvařeč třísky nástroje.

Je třeba poznamenat, že vliv posuvu je způsoben vlivem tloušťky třísky h_c. Proto se při stejném posuvu, ale v jiném úhlu K_r bude fragmentace třísky lišit, protože tloušťka třísky je závislá kromě posuvu i na tomto úhlu.

CNC obrábění

Zkratka CNC značí Computer Numerical Control, tedy číslicově řízené obrábění. CNC obrábění se liší od konvenčního obrábění tím, že vzájemný pohyb nástroje a obrobku je numericky řízen počítačem. Zatímco konvenční obrábění je ovládáno ručně, CNC obrábění je částečně nebo plně automatizované. CNC obrábění představuje automatizaci obráběcích strojů [3].

Struktura CNC stroje je podobná struktuře konvenčních obráběcích strojů, ale obecně je složitější. Kromě struktury konvenčního stroje obsahuje CNC stroj také složité systémy řízení pohybu a množství senzorů (detektorů). Pohyby jsou obvykle řízeny servomotory, které jsou schopné přesných pohybů.

Závity

Závitové spoje jsou metodou spojování dílů.

Závity vytváří šroubovou vazbu mezi komponenty se závity a toto spojení mění rotační pohyb na lineární pohyb [4].

Šroubovice je křivka vytvořená sledováním polohy bodu A na válcové ploše se dvěma současnými pohyby:

- rotace XY bodu A kolem osy válce,
- translační pohyb rovnoběžný s osou válce [5].

Závitové spoje

Závitové spoje jsou způsob, jak spojit dvě součásti dohromady pomocí upevnění závitem. Nejběžněji známým příkladem závitového spoje je šroub a matice. Závitové spoje jsou důležitým typem spojů, protože je šroubový spoj demontovatelný [4].

Výhodou montáže pomocí závitových spojů jsou:

- sestava je demontovatelná,
- závity jsou standardizované,
- závitové spoje jsou odolné vůči silám ve více směrech (v závislosti na typu závitu).

Jak vnější, tak vnitřní závity jsou důležitými funkčními prvky součástí studovaných v této práci.

Typy závitů

Existuje mnoho mezinárodně normalizovaných profilů závitů, například [6]:

- závit ISO (metrický),
- lichoběžníkový závit,
- Whitworthův,
- trubkový.

Ve studované části jsou obráběny pouze metrické závity.

Výroba závitů

Existuje několik způsobů vytvoření závitů, například:

- obrábění,
- tváření,
- 3D tisk,
- odlévání.

V bylo porovnáno vytváření závitů pomocí tvářecích závitníků a pomocí obrábění.

Výroba vnitřních závitů pomocí tvářecích závitníků

Výroba závitů za pomoci tvářecí závitníky nespadá pod třískové obrábění, protože závit je místo obrábění tvářen a žádné třísky nevznikají. Materiál je závitníkem postupně tvářen do profilu závitu. Výhodou je zvýšení tvrdosti povrchu vyrobené závitu způsobeného deformací. Vyrobený závit je tedy více odolný vůči opotřebení, abrazi.

Vnitřní tváření závitů pomocí závitníku je spojeno s rizikem zalomení nástroje v díře. Pokud se závitník v díře zalomí, odstranění závitníku ze součásti je komplikované a často může součást nevratně poškodit. Proto není vhodné používat tvářecí závitníky pro součásti s velkou přidanou hodnotou (například velké součásti, které byly dlouho obráběny). Aplikace jiných metod je vhodnější.

Výroba závitů obráběním

Existuje několik způsobů třískového obrábění závitů, například:

- soustružení závitu,
- pomocí řezacích závitníku,
- frézování závitů,

Závitník má stejný průměr jako obráběná díra, což způsobuje riziko zalomení nástroje a poškození obráběné součásti.

1) **Soustružení závitů**

Jak vnitřní, tak vnější závity mohou být vyrobeny soustružením, pokud je závit v ose rotační součásti.

V závislosti na poloze vyměnitelné břitové destičky vůči profilu závitu jsou rozlišovány různé přísuvy.

Různé přísuvy produkují různé typy třísek pro různé materiály.

2) **Obrábění závitů řezacími závitníky**

Vnitřní závity se pomocí závitníků obrábí za posuvu, který je nutně roven stoupání vyráběného závitu. Závitníky musí mít stejný průměr jako závitový otvor [7].

Existuje riziko zlomení nástroje v díře. Protože závitníky mají stejný průměr jako obráběná díra, je vyjmutí zlomeného závitořezného nástroje obtížné a často vede ke zničení obrobku.

Dlouhé nefragmentované třísky jsou také typické při řezání závitů závitníkem. Lepší fragmentaci třísek lze dosáhnout alternativní metodu – frézováním závitů.

3) **Frézování závitů**

Jak vnější, tak vnitřní závity mohou být obráběny frézováním. Průměr nástroje je menší než průměr obráběné díry.

Frézování závitů je dobře použitelné i pro těžko obrobitelné materiály [8].

Automatizace v daném průmyslovém kontextu

Automatizace obráběcího procesu představovala cíl do budoucna a nebyla cílem této studie. Tato studie je prvním krokem k umožnění automatizace procesu obrábění zajišťovacích šroubů. Na začátku této studie nebyl proces obrábění možný bez neustálého dohledu operátora, což vyloučilo možnost automatizovat výrobní proces. V této studii budou možnosti automatizace pro daný obráběcí stroj diskutovány pouze krátce jako předběžná práce pro pokračování na základě dosažených výsledků.

Nedostatky současného výrobního procesu vzhledem k automatizaci jsou:

- stroj je zastaralý (z roku 2003),
- automatizované podávání obrobků je požadováno pouze pro jednu skupinu dílů, zatímco stroj se používá i k obrábění jiných součástí,
- komponenty jsou vyráběny v malých sériích a série vyráběna každý týden se liší podle požadavků klienta.

Protože je stroj zastaralý, nejsou splněny některé kritické podmínky pro automatizaci, například:

- staré softwarové rozhraní není dostatečné pro komunikaci s robotem,
- nedostatečná paměť stroje,
- absence automatického seřizovače nástrojů,
- absence dotykové sondy obrobku,
- absence automatického zavírání / otevírání dveří.

Za účelem projednání možností budoucí automatizace stroje byly kontaktovány následující společnosti:

- společnost DMG Mori, která by měla na starost modernizace stroje,
- společnost TechPlus k projednání možností robotizace.

Společnost TechPlus poskytla kontrolní seznam nezbytných systémů přítomných na stroji.

Náklady na modernizaci a dovybavení stroje mohou být překážkou a vyvstává otázka, pokud by pořízení nového, přizpůsobenějšího stroje nebylo vhodnější pro automatizovaný proces obrábění, než investice do dovybavení původního CNC stroje.

Problémy identifikované ve výrobě

Následující problémy byly zaznamenány při obrábění zajišťovacích šroubů:

- **Hrubování vnější válcové plochy:** nedělené třísky,
- **Dokončování vnější válcové plochy a soustružení kontury:** nedělené třísky, dlouhé třísky motající se na nástroj a obrobek,
- **Soustružení vnitřní válcové plochy (hrubování):** nedělené třísky, dlouhé třísky motající se na nástroj,
- **Soustružení vnitřní válcové plochy (dokončování):** vrtání předcházející soustružení vnitřní válcové plochy zanechalo na dně díry nerovný povrch, během dokončování často docházelo ke zničení vyměnitelné břitové destičky,
- **Soustružení vnějšího metrického závitu:** za použití radiálního přísuvu byly vzniklé třísky nedělené, dlouhé, namotané na obrobek; operátor musel třísky odstranit, jinak zablokovaly dopravník třísek,
- **Řezání vnitřních závitů závitníkem:** dlouhé třísky namotané na nástroj, nutný zásah operátora po každém obrobeném závitu.
- **Soustružení vnitřního závitu:** dlouhé třísky zaseknuté v díře po obrobení závitu, vibrace během obrábění, fazetky způsobené vibracemi na obrobeném povrchu závitu.

Experimenty

Byly definovány následující experimenty:

1) experimentální studium tvrdosti obráběného materiálu,
2) fragmentace třísek během soustružení při hrubování vnějšího válcového průměru,
3) fragmentace třísek během soustružení při dokončování vnějšího válcového průměru,
4) fragmentace třísek během vnitřního soustružení (hrubování a dokončování),
5) frézování vnitřních závitů,
6) soustružení vnějšího závitu,
7) trochoidní frézování kapsy,
8) další méně obsáhlé experimenty.

Výsledky studie tvdosti obráběného materiálu

Tvrdost obrobků z materiálu 30CrNiMo8 + QT byla mezi mezemi pevnosti v tahu zaručenými normou NF EN ISO 683-2.

Meze pevnosti v tahu této oceli je dle normy NF EN ISO 683-2 mezi 930 a 1130 MPa. Mezi pevnosti v tahu lze přiřadit přibližnou odpovídající tvrdost. Pro vymezené hodnoty je odpovídající hodnota tvrdosti Brinella mezi 271 a 327 HB (při použití ocelové kouličky o průměru 10 mm a síly 3000 kg [9].

Tvrdost byla měřena pomocí přístroje Equotip Piccolo 2, který měřil tvrdost dle Leeba. Zařízení samotné převádí hodnoty v HL na tvrdost Brinella HB, nastavení zařízení bylo nastaveno na tvrdost Brinella protože je to firmou preferovaná stupnice tvrdosti. Je třeba poznamenat, že překlad mezi stupnicí tvrdosti je empirický pomocí překladových tabulek a hodnoty tedy nejsou přesnými ekvivalenty.

Studie tvrdosti vybraných obrobků ukazuje, že dodavatel dodal vyhovující materiál, který respektoval normu.

Materiál obrobku má variabilní tvrdost, což může mít vliv na obrobitelnost. Pro další experimenty byla jako výchozí hodnota brána nejvyšší možná tvrdost materiálu (327 HB). Při výběru nástrojů a řezných parametrů byla stanovena hypotéza, že vyšší tvrdost v tomto rozmezí hodnot vede k horší obrobitelnosti.

Ve všech studovaných obrobcích byla tvrdost nižší směrem ke středu obrobku.

Výsledky při hrubování vnější válcové plochy

Doporučení pro hrubování vnějších průměrů zajišťovacích šroubů jsou následující na základě výsledků fragmentace třísky a studie výkonu následující:

Pro hrubování vnějšího průměru se doporučuje použít novou řeznou destičku CNMG 16 06 16 RP5 WPP10S od firmy Walter Tools za následujících řezný podmínek:

- a_p = 3.5-4.5 mm v závislosti na obráběném poloměru.
- f_{max} = 0.50 mm,
- v_c = 140 m/min (výchozí hodnota, je vhodné otestovat životnost nástroje za různých řezných rychlostí).

Původní řezné podmínky pro šroub HP3 byly:

- $a_{p,\ original}$ = 3,0 mm,
- $f_{original}$ = 0,32 mm,
- v_c = 180 m/min.

Za původních řezných podmínek byl obráběcí čas $T_{roughing,HP3,\ original}$ = 18 min 59 s.

Pokud by nové řezné podmínky byly:

- $a_{p,\ new}$ = 4,5 mm,
- f_{new} =0,5 mm
- v_c = 130 m/min.

Nový obráběcí čas by za výše uvedených podmínek byl $T_{roughing,HP3, new, vc130}$ = 10 min 29 s. Nový obráběcí čas by byl o 45% nižší než původní obráběcí čas.

Pokud by nové řezné podmínky byly:

- $a_{p, new}$ = 4,5 mm,
- f_{new} =0,5 mm
- v_c = 140 m/min.

Nový obráběcí čas by za výše uvedených podmínek byl $T_{roughing,HP3, new, vc130}$ = 9 min 26 s. Nový obráběcí čas by byl o 51% nižší než původní obráběcí čas.

Pokud by nové řezné podmínky byly:

- $a_{p, new}$ = 4,5 mm,
- f_{new} =0,5 mm
- v_c = 150 m/min.

Nový obráběcí čas by za výše uvedených podmínek byl $T_{roughing,HP3, new, vc150}$ = 8 min 49 s. Nový obráběcí čas by byl o 54% nižší než původní obráběcí čas.

Pro stanovení optimální řezné rychlosti se doporučuje provést studii životnosti nástroje při různých řezných rychlostech.

Při obrábění průměrů větších než 280 mm je nutné použít nižší řezné parametry, aby se vešly do mezních hodnot momentu NC stroje. Například největší zajišťovací šroub HP6 může být hrubován následujícím způsobem.

Původní řezné podmínky pro šroub HP6 byly:

- a_{p1}= 3 mm,
- f_1 =0,3 mm,
- v_c = 180 m/min,
- T = 55 min 13s,

Za původních řezných podmínek byl obráběcí čas $T_{roughing, HP6, original}$ = 55 min 13 s.

Nová strategie obrábění šroubu HP6 je rozdělena do 2 fází, první fáze je na větší části průměru obrobku.

Fáze 1:

- a_{p1}= 3 mm,
- f_1 =0,3 mm,
- v_c = 180 m/min,
- T = 21 min,
- n_{passes} = 7.

Fáze 2:

- a_{p1}= 4,5 mm,
- f_1 =0,45 mm,
- v_c = 140 m/min,
- T = 19 min 42 s,
- n_{passes} = 9.

Dvoufázové hrubování šroubu HP6 bylo testováno ve výrobě s dobrou celkovou fragmentací třísek a přijatelnou spotřebou energie.

Nový obráběcí čas za výše uvedených podmínek byl $T_{roughing, HP6, new, vc140}$ = 40 min 42 s. Nový obráběcí čas byl o 27% nižší než původní obráběcí čas.

<u>Výsledky při dokončování vnější válcové plochy</u>

Doporučení pro dokončování vnějších průměrů zajišťovacích šroubů jsou na základě výsledků fragmentace třísek následující.

Pro dokončování je doporučena nová vyměnitelná břitová destička VNMG 16 04 04-FP5 WPP20S od společnosti Walter Tools.

U soustružení profilů by měl být použit přizpůsobený posuv. Studie fragmentace třísky zvažovala pouze soustružení válcového povrchu s úhlem Kr = 93 °. Při soustružení profilu se úhel Kr mění s ní i tloušťka třísky, která má vliv na lámavost třísky. Břitová destička VNMG 16 04 04-FP5 WPP20S měla při obrábění nejlepší fragmentaci třísky a to i při nízkém posuvu, a proto byla shledána jako nejvhodnější.

Původní řezné podmínky byly pro dokončování:

- $a_{p, original}$ = 1 mm,
- $f_{original}$ = 0,30 mm,
- v_c = 200 m/min.

Za použití původní břitové destičky a původních řezných podmínek byly vytvářeny velmi dlouhé nefragmentované třísky, které se motaly na nástroj i na obrobek.

Nové řezné podmínky pro břitovou destičku VNMG 16 04 04-FP5 WPP20S byly doporučeny:

- $a_{p, new}$ = 0,8 mm (testovaný limit, lze zvýšit),
- f_{new} = 0,25 (testovaný limit, lze zvýšit),
- v_c = 180 m/min (testovaný limit, lze zvýšit).

<u>Výsledky pro vnitřní soustružení</u>

Doporučení pro vnitřní soustružení byla stanovena následovně.

Pro hrubování je doporučeno použít původní stejnou řeznou destičku (Sandvik CNMG 12 04 12-PR 4225) za použití nových řezných podmínek:

- a_p = 3 mm,
- f = 0,35 mm,

- v_c = 140 m/min (výchozí hodnota, je vhodné otestovat životnost nástroje za různých řezných rychlostí).

Pro dokončování je doporučena vyměnitelná břitová CNMG 12 04 12-FP5 WPP20S za použití následujících řezných podmínek:

- a_p = 1,2 mm,
- f = 0,17 mm nejméně,
- v_c = 180 m/min (výchozí hodnota, je vhodné otestovat životnost nástroje za různých řezných rychlostí).

Výsledky pro frézování vnitřních závitů

Pro frézování vnitřních závitů byly použity celokarbidové nástroje tak nástroje s vyměnitelnými břitovými destičkami.

Třísky byly v obou případech dělené a byly snadno odváděný řeznou kapalinou. Právě excelentní lámavost třísky byla důvodem pro použití této technologie k výrobě vnitřních závitů. Původní strategie obrábění těchto závitů bylo soustružení a obrábění závitů závitníky. Obě původní strategie měly za následek dlouhé třísky, které musel operátor manuálně odstranit jak z nástroje, tak z obráběné díry.

Frézování závitů mělo za následek o několik sekund až desítek sekund delší obráběcí čas, ale tato časová ztráta byla vykompenzována díky snadnému odvodu třísek, díky které operátor nemusel zastavovat stroj a odstraňovat třísky.

Výsledky pro frézu s vyměnitelnými břitovými destičkami

Vyrobený závit splňoval rozměrové tolerance a povrch závitu byl bez vad a náznaku vibrací.

Hlavním cílem této nové strategie byla lepší typologie třísky a snadný odvod třísky. Výsledné přijatelné třísky představovaly znatelné zlepšení ve srovnání s původní metodou soustružení vnitřního závitu.

Obráběcí čas pro výrobu závitu M30x3.5 o hloubce 50.5 mm byl:

- $T_{M30,original}$ = **31 sec** (soustružení),
- $T_{M30,new}$ = **37 sec** (frézování).

Výsledky pro celokarbidové frézy

Dvě celokarbidové frézy odlišné pouze délkou byly použity k obrobení závitů M16x2. Delší varianta byla použita pro delší vnitřní závity, které představovali menšinu obráběných děr M16x2. Pro obě varianty byly během obrábění přítomny vibrace a proto byl výsledný povrch s fazetkami. Pro kratší verzi frézy byly vibrace o něco menší. Kvalita závitu však byla přijatelná v obou případech.

Ani přechod na dvoustupňovou strategii hrubování a následného dokončování (tedy snížení hodnoty hloubky řezu) a zvyšování řezné rychlosti neeliminovalo problém s vibracemi. Obráběcí čas pro výrobu závitu M16x2 o hloubce35 mm (byl):

- $T_{M16,original}$ = **21 sec** (závitníkem),
- $T_{M16,new}$ = **35 sec** (frézování, kratší nástroj).

Obráběcí čas pro výrobu závitu M20x2.5 byl simulován následně:

- $T_{M20,original,\ simulation}$ = **21 sec** (závitníkem),
- $T_{M20,new,\ simulation}$ = **35 sec** (frézou).

1) **Výsledky vnějšího soustružení závitů**

Experimentálně bylo stanoveno, že modifikovaný (boční) přísuv během soustružení vnějšího závitu byl nejvhodnější z hlediska typologie třísek. Třísky byly méně dlouhé a byly snadno odváděny dopravníkem třísek. Původně používaný radiální přísuv měl pro daný materiál za následek velmi dlouhé třísky, které nebylo možné evakuovat dopravníkem třísek a motaly se na obrobek. Střídavý přísuv byl také vyzkoušen, ale výsledkem nebylo zlepšení typologie třísek.

2) **Výsledky trochoidního frézování**

Pro šroub HP3 původní strategie frézování kapsy o hloubce 30 mm byla obrobena strategií konturování s celkovou doba obrábění T = 4 min 53 s (pro kapsu se dvěma drážkami).

Pomocí trochoidní frézovací strategie, byla stejná kapsa obrobena za čas T = 58 s (pro obě drážky). Nový obráběcí čas byl o 81% rychlejší než původní.

U zajišťovacích šroubů, které mají 4 drážky, by ušetřený čas byl ještě výraznější.

Pro HP6 je kapsa hlubší. Je nutné použít delší verzi nástroje, proto jsou řezné parametry nižší. Původní doba obrábění byla T = 12 min 28 s (pro 4 drážky). Nová doba obrábění za použití trochoidního frézování byla T = 4 min 31 s (pro 4 drážky). Nová doba obrábění byla tedy o 64% rychlejší.

Frézovací nástroj se 4 zuby byl také vyzkoušen a vedl k mnohem lepšímu odvodu třísky, ale bylo nutné použít nižší řezné parametry (proto byla doba obrábění delší) a nástroj měl tendenci vibrovat o něco více než verze s 5 zuby.

Pro budoucí použití ve výrobě se doporučuje nástroj s 5 zuby s poloměrem 2 mm na špičce a přívodem řezné kapaliny k lepší evakuaci třísek.

Diskuze

Dílčí poznámky byly uvedeny na konci jednotlivých sekcí popisující provedené experimenty.

Přestože ekonomická optimalizace nebyla předmětem této práce, v průmyslovém kontextu je ušetření výrobních nákladu vhodné.

Hrubování zajišťovacích šroubů je důležitá operace, která představuje více než třetinu celkového času obrábění studovaných součástí, a tedy i značnou část výrobních nákladů zajišťovacích šroubů. Proto by hrubování mělo být studováno více, zejména ohledně řezné rychlosti a jejího vztahu k životnosti nástroje, který ovlivňuje náklady na obrábění. Hodnota řezné rychlosti nastavená během experimentů by měla být použita jako výchozí hodnota a mělo by se testovat více řezných rychlostí.

Obecně platí, že zvýšení řezné rychlosti snižuje životnost nástroje, ale součást je obrobena rychleji. Ekonomicky optimální hodnota řezné rychlosti $v_{c,\ optimal}$ by měla být hledána. Při této hodnotě řezné rychlosti se kompenzuje kratší životnost nástroje kratším obráběcím časem [22].

Jakmile je známa životnost břitových destiček, lze automatickou výměnu nástroje naprogramovat ve správných intervalech. Automatický měnič nástrojů může obsahovat dva identické nástroje a zásah operátora by tedy nebyl nutný.

Ve výrobě je vhodné implementovat všechny změny strategií obrábění, nové nástroje a nové řezné podmínky. V programech CAM je třeba provést změny. Doporučuje se nejprve provést všechny změny na jednom vybraném modelu šroubu a posoudit, zda byly odstraněny všechny problémy během obrábění, nebo zda jsou nutné další změny. Jakmile bude proces obrábění tohoto šroubu potvrzen ve výrobě, lze strategie a řezné podmínky rozšířit na všechny modely zajišťovacích šroubů.

Jakmile budou nové programy CAM vytvořeny a vygenerované NC programy budou testovány ve výrobních závodech s potvrzením dobré odvodu třísek pro každou fázi obrábění, lze zvažovat investici automatizace. Studie návratnosti investice by měla být vypočtena.

Před zavedením automatizovaného systému podávání obrobku je třeba modernizovat CNC stroj, který je pro takovou technologii zastaralý. Možný nárůst velikosti série zajišťovacích šroubů představuje možnost rychlejšího návratu investic.

Závěry

Nové nástroje a nové obráběcí strategie byly navrženy, aby se během obrábění dosáhlo přijatelné fragmentace třísek a, které lze snadno odvádět a nebrání budoucí automatizaci procesu.

Fragmentace třísek byla zlepšena pro několik technologií:

- válcového soustružení s vyměnitelnými břitovými destičkami CNMG, kde byla doporučena nová destička,
- dokončování a konturování vyměnitelnou břitovou destičkou VNMG, kde byla také doporučena nová destička,
- vnitřní soustružení vyměnitelnou břitovou destičkou geometrie CNMG, kde doporučeno zachovat původní destičku, ale upravit řezné podmínky,
- soustružení vnějšího závitu – změna přísuvu,
- vnitřní soustružení závitů bylo nahrazeno strategií frézování pomocí frézy s vyměnitelnými břitovými destičkami,
- obrábění vnitřních závitů závitníkem bylo nahrazeno frézováním za pomoci celokarbidové frézy.

Nakonec bylo dosaženo velmi přijatelná lámavost třísek a odvod třísek. Kromě toho byly potvrzeny následující příznivé výsledky obrábění s dopadem zejména na ekonomiku procesu:

- nové břitové destičky a vhodné řezné podmínky pro hrubovací soustružení vedly k výrazně kratším obráběcím časům. U zajišťovacího šroubu HP3 bylo snížení doby obrábění nejméně o 45% (při použití řezné rychlosti ≥ 130 m /min) a u zajišťovacího šroubu HP6 bylo snížení doby obrábění nejméně o 27%.
- navíc bylo zapotřebí výrazně menší řezné síly ve srovnání s původními hrubovacími břitovými destičkami;
- moderní strategie frézování kapes pomocí trochoidních trajektorií vedla k výrazně kratší době obrábění se zkrácením obráběcího času v rozmezí 60-80%.

Zlepšení obráběcího procesu představovala první, ale velmi zásadní krok pro budoucí automatizaci obráběcího procesu. Vynikající fragmentace třísek eliminuje zásahy obsluhy, která před optimalizací musela často odstraňovat třísky navinuté nástroje i obrobek nebo zprovozňovat dlouhými třískami blokovaný dopravník třísek. Výsledky diplomové práce podporují stabilitu a kontinuitu výroby.

ABSTRAIT

Introduction

Cette thèse a été élaborée lors d'un stage dans l'entreprise Metso à Mâcon en France où sont fabriqués les concasseurs coniques Metso. Les objectifs du stage étaient d'optimiser le processus d'usinage de la fabrication d'une famille de composants sur une machine à commande numérique de type tour-fraise multifonctionnel. Les composants étudiés étaient déjà en production depuis de nombreuses années. L'automatisation future du processus d'usinage a été considérée comme un investissement, mais au début de ce stage, l'automatisation n'était pas possible car le processus d'usinage n'était pas optimisé. L'aspect le plus important à optimiser était la fragmentation des copeaux. Les longs copeaux non fragmentés ont éliminé toute possibilité d'automatisation future.

Les pièces étudiés, appelés vis de blocage ou vis de tête sont des vis de grandes dimensions et sont des composants des concasseurs à cône Metso.

Les agrégats doivent être broyés à la taille requise. La réduction de la taille des agrégats se fait progressivement en plusieurs étapes. Le concasseur à cône est un type de concasseur utilisé pour réduire la taille des agrégats et est généralement utilisé pour le concassage secondaire, tertiaire ou quaternaire [1].

Les vis sont des composants mécaniques qui servent à créer des joints filetés. Généralement deux parties d'un vis peuvent être différenciés : la tête et le diamètre du filetage. Les vis peuvent être de différentes tailles, mais les plus utilisées et connues sont les vis de dimensions considérablement petites. Par exemple, les vis utilisées pour l'assemblage de meubles n'ont que quelques millimètres de diamètre et ne font que quelques dixièmes de millimètres de long. Les vis de petites dimensions sont généralement fabriquées par forgeage à froid d'un morceau de fil, suivi d'un filetage [2].

Des vis de grande dimension sont d’habitude fabriquées avec différentes technologies. Dans cette thèse, la fabrication de vis de grandes dimensions (diamètre de filetage supérieur à 100 mm) par coupe a été élaborée.

Les vis de blocage chez Metso à Mâcon ont été fabriquées en petites séries au début du stage. L'état de l'art au début de ce projet est un processus d'usinage qui doit toujours être supervisé par l'opérateur. L'augmentation du niveau d'automatisation a été fixée comme objectif. L'augmentation de l'autonomie permettrait à l'opérateur d'effectuer d'autres tâches, par exemple de travailler sur une autre machine. L'automatisation partielle ou totale du processus d'usinage et la robotisation sont considérées comme un investissement possible. En outre, la taille des séries peut être augmentée en raison de la délocalisation de la production d'autres sites de fabrication. Une plus grande taille des séries ferait de l'automatisation un meilleur retour sur investissement. Le processus de coupe doit être optimisé. L'optimisation du processus de coupe a été menée selon des critères d'autonomie, le but étant de minimiser l'intervention de l'opérateur pendant le processus d'usinage. L'automatisation et la robotisation futures sont une suite possible de ce projet.

Typologie des copeaux

Les copeaux continus sont longs et ne sont pas fragmentés. Les copeaux continus ne se forment que lors d'opérations d'usinage avec une coupe continue et une épaisseur de copeau constante, le meilleur exemple étant le tournage, mais les copeaux continus sont également observables lors du perçage ou du taraudage [3].

La fragmentation des copeaux est souhaitée parce que [10] :

- les copeaux continus sont dangereux pour l'homme à proximité de la machine,

- Les copeaux continus peuvent endommager la surface usinée,

- les copeaux continus peuvent endommager les machines

- Les copeaux fragmentés sont plus faciles à stocker,

- Les copeaux fragmentés sont plus facilement évacués par le fluide de refroidissement et de lubrification et permettent l'écoulement du fluide de refroidissement et de lubrification vers l'outil, ce qui augmente la durée de vie de l'outil.

Les paramètres de coupe qui influencent le plus la fragmentation des copeaux pendant le tournage sont :

- la profondeur de coupe,
- l’avance,
- la vitesse de coupe,
- la lubrification,
- le brise-copeaux sur la plaquette de coupe.

Il convient de noter que l'influence de l'avance est plus une influence de l'épaisseur du copeau h_c, C'est pourquoi à la même avance mais à un angle différent K_r la fragmentation du copeau sera différente.

CNC machining

L'abréviation CNC signifie "Computer Numerical Control" (commande numérique par ordinateur). L'usinage CNC est différent de l'usinage conventionnel car le mouvement de l'outil ou de la pièce est commandé numériquement par un ordinateur. Alors que l'usinage conventionnel est contrôlé manuellement, l'usinage CNC est partiellement ou entièrement automatisé. La commande numérique par ordinateur représente une automatisation des machines-outils [3].

La structure de la machine CNC est similaire à celle des machines conventionnelles, mais elle est généralement plus complexe. En plus de la structure d'une machine conventionnelle, une machine CNC contient également des systèmes complexes de contrôle de mouvement et une multitude de capteurs (détecteurs). Les mouvements sont généralement contrôlés par des servomoteurs capables de mouvements précis.

Stratégie de fraisage trochoïdale

La trochoïde est une famille de courbes et un type de cycloïde (lieu d'un point à une distance d'un cercle roulant autour d'une ligne droite) [11, 12].

Lors du fraisage trochoïdal, le mouvement d'avance se fait dans la direction de la trajectoire trochoïdale.

Dans les contextes industriels, en particulier pour les stratégies de ébauche, il est nécessaire d'éliminer de grands volumes de matière en réduisant les temps d'usinage. L'optimisation de la trajectoire de l'outil par fraisage trochoïdal peut répondre à de telles exigences car il s'agit d'une trajectoire continue. Le fraisage trochoïde est une stratégie mettant en œuvre un mouvement trochoïdal. Cette trajectoire élimine les accélérations et les décélérations, le mouvement de l'outil a donc une vitesse constante [13].

Le fraisage trochoïdal est très efficace même pour les matériaux durcis [14].

Filets

Les joints filetés sont une méthode d'assemblage des pièces.

Les filetages hélicoïdaux sont une méthode mécanique de création d'une liaison hélicoïdale entre des pièces filetées qui transforme un mouvement angulaire en mouvement linéaire [45].

Une hélice est une courbe créée en traçant la position du point A sur une surface cylindrique avec deux mouvements simultanés :

- rotation XY du point A autour de l'axe du cylindre,

- translation parallèle à l'axe du cylindre [5].

Les joints filetés (par exemple vis et écrous, boulons) sont un type important de joints car une fixation filetée est démontable .Les assemblages filetés sont un moyen d'assembler deux pièces par une fixation filetée. L'exemple le plus connu d'un assemblage par filetage est celui d'une vis et d'un écrou.

Dans ce cas d'étude, la fonction du joint fileté joue un rôle important pour de multiples éléments fonctionnels de la pièce étudiée.

Les avantages de l'assemblage par joints filetés sont les suivants [45]:

- L'assemblage est démontable.

- Les filetages sont largement standardisés

- Les joints filetés résistent aux forces dans plusieurs directions (selon le type de filetage)

Des joints filetés sont présents sur la partie étudiée, tant externes qu'internes.

Les filetages sont largement normalisés et il existe de nombreux types de filetages normalisés.

Sur la partie étudiée, seuls les filetages métriques (ISO) sont utilisés.

Méthodes de fabrication des fillets

Il existe plusieurs méthodes pour créer un fillet, par exemple :

- la coupe,
- - le formage (taraudage, roulage),
- - Impression 3D,
- - casting.

Le taraudage et le coupe de forme vont être comparés dans la section suivante.

Taraudage par déformation

La création d'un filetage par déformation est appelée taraudage de forme. Lors du taraudage, aucun copeau n'est créé, au contraire, la matière est peu à peu déformée pour prendre la forme du filetage. L'avantage est que la matière est durcie par cette déformation, ce qui rend le filetage plus résistant à l'usure. Pour le taraudage par déformation interne, il existe un risque de rupture de l'outil. Si l'outil de taraudage se casse dans le trou, la pièce est généralement ruinée et doit être éliminée. C'est pourquoi le taraudage n'est généralement pas utilisé pour les pièces qui ont une grande valeur ajoutée (par exemple les grosses pièces aéronautiques). D'autres méthodes sont préférées pour de telles applications.

Méthodes de coupe du filet

Méthodes de coupe du filet

D'autre part, le fait de couper un fil signifie que des copeaux sont créés. Pour le composant étudié, seul le filetage par coupe a été utilisé.

Il existe plusieurs méthodes de coupe de fil, par exemple :

- le filetage par tournage,
- le fraisage de filets,
- taraudage.

Le taraudage par filetage présente le même problème que le taraudage par déformation : si l'outil se casse à l'intérieur du trou, la pièce doit être éliminée.

Tournage des filets

Les filetages intérieurs et extérieurs peuvent être réalisés par tournage si le filetage est concentrique à l'axe de la pièce dans laquelle se trouve la rotation des pièces pendant une opération de tournage.

Les filetages à droite et à gauche peuvent être réalisés par tournage.

En fonction de la position de la plaquette de filetage à chaque passe, différentes passes sont possibles.

Les différentes modes de pénétration produisent différents types de copeaux pour différents matériaux [15].

Fraisage des filets

Le fraisage de filets est une méthode d'usinage de filets. Je peux fraiser aussi bien des filets extérieurs que des filets intérieurs.

Le fraisage de filets est bien applicable même pour les matériaux difficiles à usiner [8].

La fraise à fileter suit une trajectoire hélicoïdale.

En raison des interférences pendant le fraisage du filet, le profil du filet généré (GTP) et le profil nominal du filet (NTP) ne sont pas égaux. Entre GTP et NTP, il y a une erreur radiale, soit une sur-dépouille ou une contre-dépouille [53].

Etude de l’automatisation de processus d’usinage des vis de blocage

L'automatisation du processus d'usinage est un objectif pour l'avenir et n'était pas un objectif de cette étude. Cette étude est le premier pas vers l'automatisation du processus un jour. Au début de cette étude, le processus d'usinage n'était pas du tout optimisé, ce qui a immédiatement éliminé la possibilité d'automatiser le processus de fabrication. Dans cette étude, les possibilités d'automatisation de la machine ne seront que brièvement discutées en tant que travail préliminaire pour la poursuite du processus d'optimisation.

L'initiative d'automatiser l'alimentation des pièces pour les vis à tête a ses conditions indispensables et pose de multiples problèmes.

Les problèmes liés à l'automatisation du processus d'usinage :

- la machine est assez obsolète (depuis 2003)
- L'alimentation automatique des pièces n'est souhaitée que pour une famille de pièces, alors que la machine sert à usiner d'autres types de composants,
- Les composants sont fabriqués en petites séries et les séries fabriquées chaque semaine varient en fonction de la demande des clients.

Comme la machine est obsolète, certaines des conditions critiques pour l'automatisation ne sont pas remplies :

- l'ancienne interface logicielle n'est pas suffisante pour communiquer avec un robot,
- mémoire interne insuffisante,
- absence d'un dispositif de réglage automatique des outils,
- absence de palpeur de pièce,
- absence de fermeture/ouverture automatique des portes,

Les entreprises suivantes ont été contactées afin de discuter des possibilités d'automatisation future de la machine :

- l'entreprise DMG Mori pour discuter de la modernisation de la machine,
- de la société TechPlus pour discuter des options de robotisation.

La société TechPlus a fourni la liste de contrôle suivante des systèmes nécessaires présents sur la machine.

Le coût de la mise à niveau peut être un revers et une question se pose si l'intégration d'une nouvelle machine plus adaptée ne serait pas plus adaptée au processus d'usinage automatisé plutôt qu'un investissement dans la mise à niveau de l'ancienne machine CNC.

Problèmes en production

Les types de problèmes suivants ont été identifiés dans la production :

- **ébauche du diamètre extérieur** : copeaux non fragmentés,
- **finition du diamètre extérieur + tournage de rainures** : copeaux longs non fragmentés, collés sur l'outil et sur la pièce,
- **alésage (finition)** : trou pré-percé avant le tournage laissant une surface inférieure irrégulière, la plaquette de l'outil d'alésage se brise souvent pendant la finition du tournage de poche,
- **tournage de filets extérieurs** : les longs copeaux non fragmentés, qui bloquent le convoyeur de copeaux, doivent être coupés manuellement à l'aide de pinces,
- **tournage cylindrique - ébauche** : copeau en forme d'anneau, doit être retiré manuellement,
- **alésage (ébauche) :** copeaux non fragmentés collés sur l'outil et la pièce,
- **taraud - filetage :** des copeaux non fragmentés se collent à chaque fois sur l'outil,
- **tournage de filets intérieurs :** copeaux longs, coincés dans le trou fileté, devant être retirés manuellement, facettes sur le filet.

Experimentations

Les expérimentations suivantes ont été définies :

1) étude expérimentale de la dureté des matériaux,
2) fragmentation des copeaux lors de l'ébauche cylindrique externe,
3) fragmentation des copeaux lors de la finition cylindrique externe,
4) fragmentation des copeaux lors de l'alésage (ébauche et finition),
5) le fraisage de filets intérieurs,
6) tournage de filets extérieurs,
7) le fraisage trochoïdal,
8) des expérimentations supplémentaires si nécessaire.

Conclusions pour la dureté des bruts

La dureté des pièces en matériau 30CrNiMo8+QT varie et reste entre les limites de résistance à la traction garanties par la norme NF EN ISO 683-2.

Les limites de la résistance à la traction selon cette norme sont de 930-1130 MPa, ce qui peut être converti en un harnais approximatif de Brinell 271 à 327 HB (dureté Brinell) en utilisant une bille d'acier de 10 mm et une force de pénétration de 3000 kg [9].

La dureté a été mesurée avec Equotip Piccolo 2 qui a mesuré la dureté de Leeb. L'appareil lui-même traduit les valeurs en HL en dureté Brinell HB, les réglages de l'appareil ont été réglés sur HB car c'est l'échelle de dureté préférée de l'atelier. Il convient de noter que la traduction entre l'échelle de dureté est empirique et utilise des tables de traduction et que les valeurs ne sont pas des équivalents exacts.

L'étude de la dureté des pièces choisies montre que le fournisseur a livré un matériau conforme qui a respecté la norme.

Le matériau de la pièce est conforme mais sa dureté varie, ce qui peut avoir une influence sur l'usinabilité. Pour les expérimentations suivantes, la dureté la plus élevée du matériau a été prise en compte lors du choix des outils et des paramètres de coupe, dans l'hypothèse où une dureté plus élevée dans cette plage de valeurs entraîne une usinabilité moins bonne.

Dans toutes les pièces étudiées, la dureté était plus faible vers le centre de la pièce.

Résultats en ébauche en tournage de diamètre externe

Les recommandations pour l'ébauche des diamètres extérieurs des vis de blocage sont les suivantes, basées sur les résultats de l'étude de fragmentation des copeaux et de la puissance consommée.

Pour l'ébauche du diamètre extérieur, régulariser la nouvelle plaquette de coupe CNMG 16 06 16 RP5 WPP10S de Walter Tools et utiliser selon les conditions de coupe :

- a_p = 3.5-4.5 mm en fonction du diamètre usiné,
- f_{max} = 0.50 mm,
- v_c = 140 m/min (à utiliser comme valeur de départ et à suivre en étudiant la vie des outils en production avec différentes v_c).

Les paramètres de coupe originaux l'étaient :

- $a_{p, original}$ = 3.0 mm,
- $f_{original}$ = 0.32 mm,
- v_c = 180 m/min.

Les paramètres de coupe d'origine ont entraîné un temps d'usinage par opération d'ébauche $T_{ébauche,HP3, original}$ = 18 min 59 sec.

Envisager de nouveaux paramètres de coupe :

- $a_{p, new}$ = 4.5 mm,
- f_{new} = 0.5 mm
- v_c = 130 m/min.

Le temps d'usinage amélioré par opération d'ébauche était $T_{ébauche,HP3, new, vc130}$ = 10 min 29 sec. Le temps d'usinage à la vitesse de coupe de 130 m/min présente une diminution du temps d'usinage de 45% par rapport à la séquence de coupe initiale.

Pour les vis de blocage de diamètres supérieurs à 280 mm, des paramètres de coupe inférieurs doivent être utilisés pour s'adapter aux limites de puissance et couple de la machine. Par exemple, le plus grand boulon de verrouillage HP6 peut être réalisé comme suit.

Les conditions de coupe originales pour l'ébauche du vis de blocage HP6 étaient :

- a_{p1}= 3 mm,
- f_1 =0.3 mm,
- v_c = 180 m/min,
- T = 55 min 13s,
- n_{passes} = 7.

Le temps d'usinage par opération d'ébauche était à l'origine $T_{ébauche,\ HP6,\ original}$ = 55 min 13 sec.

La stratégie de coupe améliorée d'ébauche du vis de blocage HP6 est divisée en 2 phases, la première phase concerne la plus grande partie du diamètre de la pièce.

La phase 1 d'ébauche du vis de blocage HP6 a les paramètres de coupe suivants recommandés:

- a_{p1}= 3 mm,
- f_1 =0.3 mm,
- v_c = 180 m/min,
- T = 21 min,
- n_{passes} = 7.
- La phase 1 d'ébauche du vis de blocage HP6 a les paramètres de coupe suivants recommandés:
- a_{p1}= 4.5 mm,
- f_1 =0.45 mm,
- v_c = 140 m/min,
- T = 19 min 42 s,
- n_{passes} = 9.

L'amélioration du temps d'usinage par opération d'ébauche a été $T_{ébauche\ HP6,\ new,\ vc140}$ = 40 min 42 sec. Le temps d'usinage à la vitesse de coupe de 140 m/min présente une diminution du temps d'usinage de 27% .

<u>Résultats en finiton</u>

Les recommandations pour la finition des diamètres extérieurs des vis de blocage sont les suivantes, basées sur les résultats de la fragmentation des copeaux.

Pour la finition du diamètre extérieur, régulariser la nouvelle plaquette de coupe VNMG 16 04 04-FP5 WPP20S de Walter Tools.

Pour le tournage de profils, il convient d'utiliser une avance adaptée. L'étude de la fragmentation des copeaux n'a pris en compte que le tournage de surfaces cylindriques avec un K_r = 93°. . Lors du tournage d'un profil, l'angle K_r change. La plaquette de coupe VNMG 16 04 04-FP5 WPP20S présente les meilleures propriétés de fragmentation des copeaux, même avec de faibles avances, et est donc la plus adaptée.

Les paramètres de coupe originaux l'étaient :

- $a_{p,\ original}$ = 1 mm,
- $f_{original}$ = 0.30 mm,
- v_c = 200 m/min.

Les nouveaux paramètres de coupe pour la nouvelle plaquette de finition VNMG 16 04 04-FP5 WPP20S qui sont recommandés sont :

- $a_{p,\ new}$ = 0.8 mm (la limite testée, elle peut être augmentée),
- f_{new} = 0.25 (la limite testée, il peut être augmenté),
- v_c = 180 m/min (la limite testée, elle peut être augmentée).

Résultats pour l'alésage

Les recommandations pour les conditions de coup en alésage ont été déterminées comme suit.

Pour l'ébauche, gardez la même plaquette de coupe que dans la séquence de coupe originale (Sandvik CNMG 12 04 12-PR 4225) et utilisez de nouvelles conditions de coupe :

- a_p = 3 mm,
- f = 0.35 mm,
- v_c = 140 m/min (utiliser comme valeur de départ et suivre en étudiant la vie des outils dans la production avec différents v_c).
- Pour la finition (si elle est mise en œuvre), utiliser la plaquette Walter CNMG 12 04 12-FP5 WPP20S avec des conditions de coupe suivantes :
- a_p = 1.2 mm,
- f = 0.17 mm au moins,
- v_c = 180 m/min (utiliser comme valeur de départ et suivre en étudiant la vie des outils dans la production avec différents v_c).

Résultats de fraisage des filets

Les fraises à filetage solide et les fraises à filetage avec plaquettes de coupe produisaient toutes deux des copeaux fragmentés qui étaient facilement évacués par le liquide de coupe et dont il n'était pas possible de prélever un échantillon. L'excellente fragmentation et évacuation des copeaux était le principal objectif de cette stratégie d'usinage de filets. Dans la séquence de coupe originale, ni le taraudage ni le tournage de filets intérieurs ne produisaient de copeaux acceptables et les copeaux devaient être évacués par l'opérateur.

L'utilisation de la stratégie de fraisage de filets permettrait d'obtenir un temps d'usinage légèrement plus long mais un gain d'autonomie grâce à une grande évacuation des copeaux.

1) Résultat de fraisage des filets internes avec une fraises à plaquettes

Le filet usiné avait une dimension et une surface usinée acceptables du premier coup.

L'amélioration de la typologie des copeaux était l'objectif principal de cette nouvelle stratégie d'usinage. Les copeaux produits lors de l'expérimentation du fraisage de filets avec des outils à plaquettes de coupe étaient acceptables, fragmentés et bien évacués. Les copeaux acceptables produits représentaient une énorme amélioration par rapport au tournage de filets intérieurs dans la séquence de coupe initiale. Après le tournage de filets intérieurs, les copeaux étaient longs et devaient être retirés manuellement du trou central à l'aide de pinces.

Temps d'usinage de M30x3,5 de profondeur 50,5 mm

- Temps d'usinage de M30x3,5 de profondeur 50,5 mm était :
- $T_{M30,original}$ = **31 sec** (thread turning),
- $T_{M30,new}$ = **37 sec** (thread milling).

2) <u>Résultat de fraisage des filets internes avec des fraises monobloc</u>

Pour les deux versions de la fraise à fileter, des vibrations étaient présentes lors de l'usinage.

Même le passage à une stratégie en deux étapes d'ébauche puis de finition (ce qui diminue la vitesse Même la version la plus courte de l'outil présentait des vibrations.

Temps d'usinage de M16x2 d'une profondeur de 35 mm :

- $T_{M16,original}$ = **21 sec** (thread tapping),
- $T_{M16,new}$ = **35 sec** (thread milling).

Le temps de simulation de 4 trous filetés M20x3,5 était :

- $T_{M20,original, simulation}$ = **21 sec** (taraudage),
- $T_{M20,new, simulation}$ = **35 sec** (fraisage de filet).

<u>Résultats de tournage de filet externe</u>

Il a été déterminé expérimentalement que l'alimentation par flanc modifiée est la meilleure pour les gros filetages externes des vis de blocage était la plus adaptée pour la typologie des copeaux. La modification de l'alimentation par le flanc a permis d'obtenir des copeaux longs mais fragmentés, et les copeaux ont été facilement évacués par le convoyeur à copeaux.

Dans la séquence de coupe originale, le fraisage de la poche en utilisant la stratégie de contournage pour le vis de blocage HP3, la poche de profondeur 30 mm a été usinée par 15 passes de 2 mm et le temps total d'usinage de cette opération était de T = 4 min 53 s (pour 2 encoches).

Dans la nouvelle séquence de coupe, la même poche a été usinée en utilisant une stratégie de fraisage trochoïdale dont le temps d'usinage total était T = 58 s (pour 2 fentes). Le nouveau temps d'usinage est 81% plus rapide que le temps d'origine.

Pour les boulons de verrouillage qui ont 4 fentes, le temps gagné serait encore plus significatif.

Pour HP6, la rainure est plus profonde. La version la plus longue de l'outil doit être utilisée, donc les paramètres de coupe sont un peu plus élevés. Le temps d'usinage original était T = 12 min 28 s (pour 4 rainures). et le nouveau temps d'usinage T = 4 min 31 s (pour 4 rainures). Le nouveau temps d'usinage est environ 64% plus rapide.

L'outil de fraisage à 4 flûtes permettait une bien meilleure évacuation des copeaux mais imposait des paramètres de coupe plus faibles (donc le temps d'usinage était plus long) et l'outil avait tendance à vibrer un peu plus que la version à 5 flûtes.

Pour une mise en œuvre future en production, il est recommandé d'utiliser un outil avec une lubrification des flancs pour une bonne évacuation des copeaux et un rayon de 2 mm à la pointe. Un rayon de 2 mm est exigé et le fond de la poche.

Discussion

L'opération d'ébauche du vis de blocage est une opération importante, elle devrait donc être étudiée davantage, notamment en ce qui concerne la magnitude de la vitesse de coupe et sa relation avec la durée de vie de l'outil, ce qui affecte les coûts d'usinage. La valeur fixée lors des expérimentations devrait être utilisée comme valeur par défaut et il faudrait tester plusieurs vitesses de coupe. En général, l'augmentation de la vitesse de coupe diminue la durée de vie de l'outil, mais la pièce est usinée plus rapidement. La valeur économiquement optimale de la vitesse de coupe $v_{c,\ optimal}$ devrait être recherchée comme une valeur qui compense la durée de vie plus courte de l'outil en ayant un temps de cycle d'usinage plus court. Une fois que la durée de vie des plaquettes de coupe est connue, le changement automatique d'outil peut être programmé à intervalles corrects. Le changeur d'outil automatique peut prendre deux outils pour le même outil si nécessaire.

Tous les changements de stratégies d'usinage, les nouveaux outils et les nouvelles conditions de coupe doivent être mis en œuvre dans la production. Les changements doivent être effectués dans les programmes de FAO. Il est recommandé de mettre en œuvre tous les changements sur un modèle choisi de vis de blocage dans un premier temps et d'évaluer si tous les problèmes pendant l'usinage ont été éliminés ou si d'autres changements sont nécessaires. Une fois que le choix de l'usinage du vis de blocage est confirmé avec succès, les stratégies et les conditions de coupe peuvent être étendues à tous les modèles de vis de blocage.

Une fois que les nouveaux programmes FAO sont générés et que les programmes CN résultants sont testés en production avec confirmation d'une bonne évacuation des copeaux pour chaque phase d'usinage, la robotisation peut être considérée comme un investissement. L'étude du retour sur investissement doit être calculée avant et était. Le rééquipement de la machine CNC est nécessaire avant de mettre en place un système d'alimentation automatique des pièces qui peut être coûteux. D'autre part, l'augmentation future de la taille des séries de boulons de verrouillage présente un retour sur investissement éventuellement rapide.

Conclusions

De nouveaux outils de coupe et de nouvelles stratégies de coupe ont été testés pour obtenir une fragmentation acceptable des copeaux pendant l'usinage, ce qui permet d'obtenir des copeaux courts faciles à évacuer et à transporter.

La fragmentation des copeaux a été optimisée pour plusieurs technologies :

- l'ébauche de tournage cylindrique avec des plaquettes de coupe CNMG où une nouvelle plaquette de coupe était recommandée,
- la finition et le contournage avec une plaquette de coupe VNMG où une nouvelle plaquette de coupe a également été recommandée,
- l'opération d'alésage avec la plaquette CNMG où la plaquette originale a été préservée, mais les conditions de coupe ont été modifiées pour améliorer les résultats,
- le tournage du filet extérieur - en changeant le mode d'alimentation en mode d'alimentation par flanc modifié,
- le tournage de filets intérieurs en remplaçant la stratégie de tournage par un fraisage plus productif utilisant des fraises à fileter et des plaquettes de coupe,
- le taraudage de filets intérieurs en remplaçant les outils de taraudage par des fraises à filetage solid et des stratégies d'usinage.

Enfin, une fragmentation et une évacuation des copeaux très acceptables ont été obtenues. En outre, les résultats bénéfiques suivants de l'usinage avec impact sur l'économie ont été confirmés :

les nouvelles plaquettes de coupe et les conditions de coupe optimisées pour le tournage d'ébauche ont permis de réduire considérablement les temps d'usinage. Pour le visde blockage HP3, la réduction du temps d'usinage a été d'au moins 45 % (en utilisant la vitesse de coupe ≥ 130 m/min) et, pour le vis de blockage HP6, la réduction du temps d'usinage a été d'au moins 27 %.
- En outre, la puissance de coupe nécessaire était nettement inférieure à celle des plaquettes de coupe d'ébauche d'origine ;
- une stratégie très moderne de fraisage de poche utilisant les trajectoires trochoïdales a permis de réduire considérablement le temps d'usinage, de sorte que la réduction du temps était de l'ordre de 60 à 80 %.

Les optimisations constituent la première étape, mais très cruciale, de l'automatisation attendue du processus d'usinage. L'excellente fragmentation des copeaux élimine les problèmes qui entraînent l'interruption de séquence d’usinage lorsque l'opérateur doit enlever des copeaux qui s'enroulent autour de l'outil, de la pièce ou qui se bloquent dans le convoyeur de copeaux. Les résultats du cette thèse favorisent une grande stabilité et la continuité de la production.

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AFFIRMATION

I declare that this master's thesis is result of my own work, led by my supervisor, and all used sources are duly listed in bibliography. I proclaim that all presented information is true and valid to the best of my knowledge.

29.08.2020

Date

Veronika Soukupová

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CONTENTS

INTRODUCTION

This thesis was elaborated during an internship at the company Metso in Mâcon in France where Metso conical crushers are fabricated. The goals of the internship were to optimise machining process of fabrication of a family of components on a turn mill CNC machine. The studied components were already on production for many years. Future automation of the machining process was considered as an investment but at the beginning of this internship automation was not possible because the machining process was not optimised. The most important aspect to optimise was chip fragmentation. Long unfragmented chips eliminated possibility to automate in the future.

The studied bolts called locking bolts or head bolts are screws of large dimensions and are components for Metso cone crushers.

Aggregates need to be crushed to the needed size. Reduction of the size of aggregates is done gradually in multiple steps. Cone crusher is a type of crusher used to reduce size of aggregates and are usually used for secondary, tertiary or quaternary crushing [1].

Screws are mechanical components that are used to create threaded joints. Two parts of a crew can usually be differentiated: head and the threaded diameter. Screws can be of different sizes, but the most used and known are screws of considerably small dimension. For example, screws that are used for assembling furniture have only a few millimetres in diameter and are just a few tenths of millimetres long. Screws of small dimension are usually fabricated by cold forging a piece of wire, followed by threading [2].

Screws of large dimension are fabricated with different technologies. In this thesis, fabrication of bolts of large dimensions (threaded diameters larger than 100mm) by cutting was elaborated.

Locking bolts at Metso in Mâcon were fabricated in small series at the beginning of the internship. The state of the art at the beginning of this project is a machining process that always needs to be supervised by the operator. Increasement in level of automation was set as an objective. Increase in autonomy would liberate the operator to perform other tasks, for example work on another machine. Partial or total automation of the machining process and robotization are considered as possible investment. Moreover, the size of the series may be increased due to relocation of production from other fabrication sites. Larger size of series would make automation a better return of investment. The cutting process needed optimizing. Optimizing the cutting process was conducted by criteria of autonomy, the goal was to minimize intervention of the operator during the machining process. Future automatization and robotization is a possible follow-up of this project.

1 THEORETICAL ANALYSIS

1.1 MACHINING

Machining is an ensemble of manufacturing processes which purpose is to eliminate part of workpiece material to obtain a product with desired geometry. The material that is machined of is called machining allowance. The workpiece before machining can be bulk material like cut rounds or more complicated solid fabricated by some other process. Parts fabricated by casting and forming usually require machining processes to obtain better precision and surfaces for example for assembly [10, 16].

Conventional or traditional machining is a term designating a machining process performed by a tool. This tool must have a much higher hardness than the machined material to cut it. The tool penetrates the material in a certain depth when in relative motion to the material [16].

1.1.1 Conventional machining

When mentioning machining in this study, conventional machining by cutting is referred to even though other non-conventional methods exist.

There are two physical principles of conventional machining [16]:

- cutting,
- mechanical abrasion.

For conventional machining by cutting tools with defined cutting tool geometry are used. Their shape can be clearly geometrically defined, for example turning inserts can be described by multiple angles and radii [17].

Conventional machining using mechanical abrasion uses tools with undefined cutting-edge geometry. For example, the grains of abrasive on a grinding gear are not geometrically united, each grain has a different shape and size. [17]

There are three principal machining processes by cutting to be distinguished [18]:

- turning,
- milling,
- drilling.

This classification is determined by the materialisation of the surface directrix. For turning, the directrix has a circular form and is generated by cutting movement. In case of milling, the directrix is generally of linear nature and is realised by feed motion. For drilling the directrix has a circular form and is generated by the cutting motion [19].

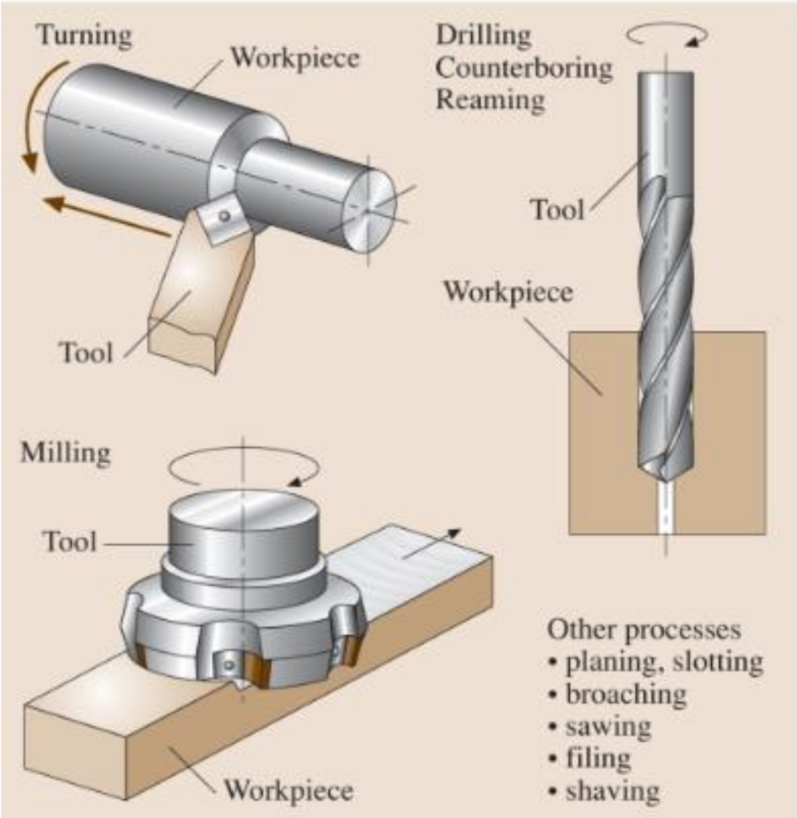


Figure 1.1.1.1 Main cutting processes with defined cutting-edge [20].

There are other machining processes of conventional machining by cutting, they are classified on the following graphic representation classified by the two physical principles (cutting and abrasion) [16].

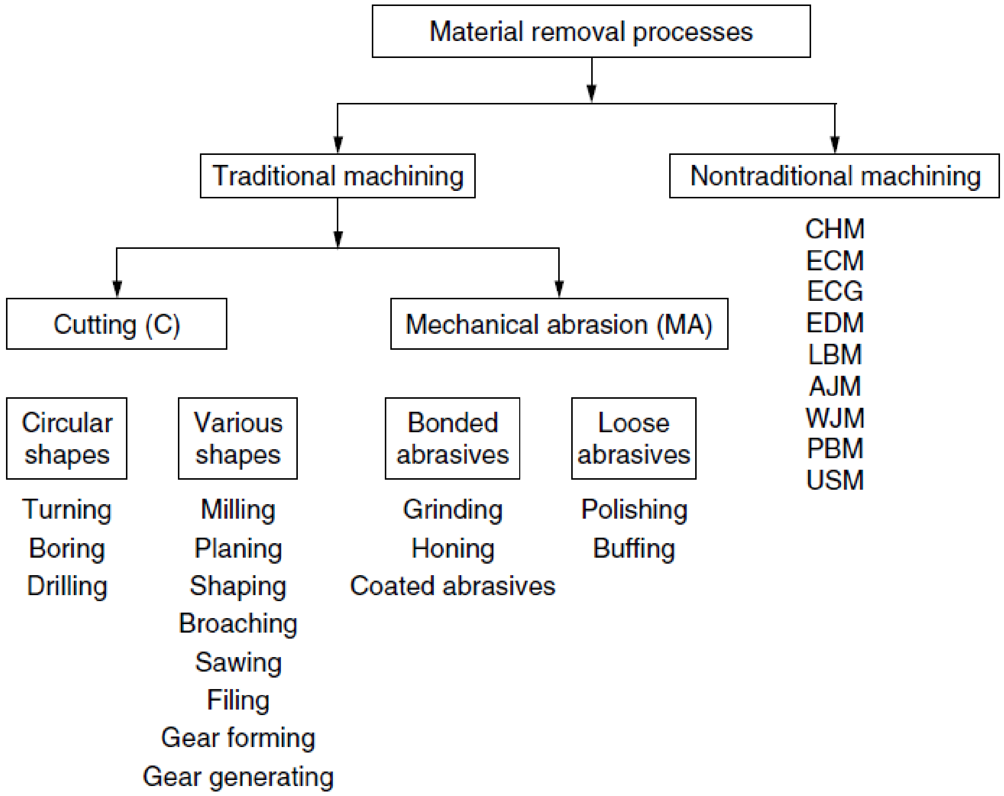


Figure 1.1.1.2 Material removal technologies [16].

In general, there are five intervening elements during machining [19]:

- workpiece,
- tool,
- toolholder,
- machine,
- workpiece support.

1.1.2 Turning

Turning is a machining process where the workpiece is in rotational movement (main) and the cutting tool performs the feed (secondary) movement. Only one cutting edge is working at a time. Therefore, the cutting tends be of continuous nature. This cutting edge is called primary or major cutting edge [17].

The workpiece for turning is of round rotational nature [19].

Turning machines are called lathes.

Turning operations can be differentiated into two categories:

1) external turning,
2) internal turning.

Main external turning operations are [10, 17]:

- cylindrical turning,
- facing,
- taper turning,
- parting (cutting off),
- recessing,
- chamfering,
- form turning,
- copy turning,
- external thread turning.

Example of cylindrical turning is drawn of the following figure:

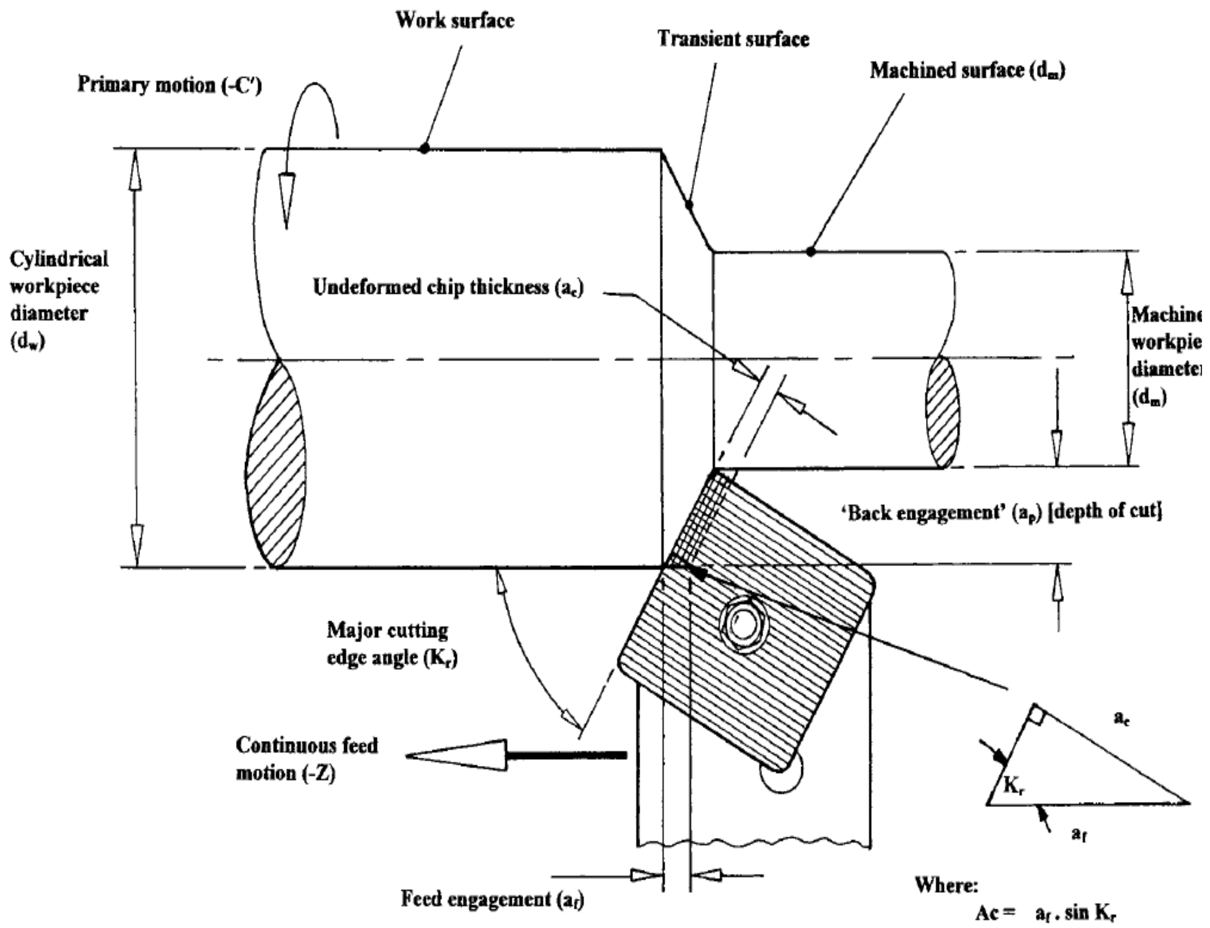


Figure 1.1.2.1 Cylindrical turning [21].

Where abbreviations have following meaning and units:

- K_r … major cutting edge angle [°] ,
- a_p … depth of cut [mm],
- a_f … feed engagement [mm],

- a_c (or h_c) … undeformed chip thickness [mm],
- d_w … workpiece diameter [mm],
- d_m … machined diameter [mm].

Principle of a facing operation is drawn in the following figure:

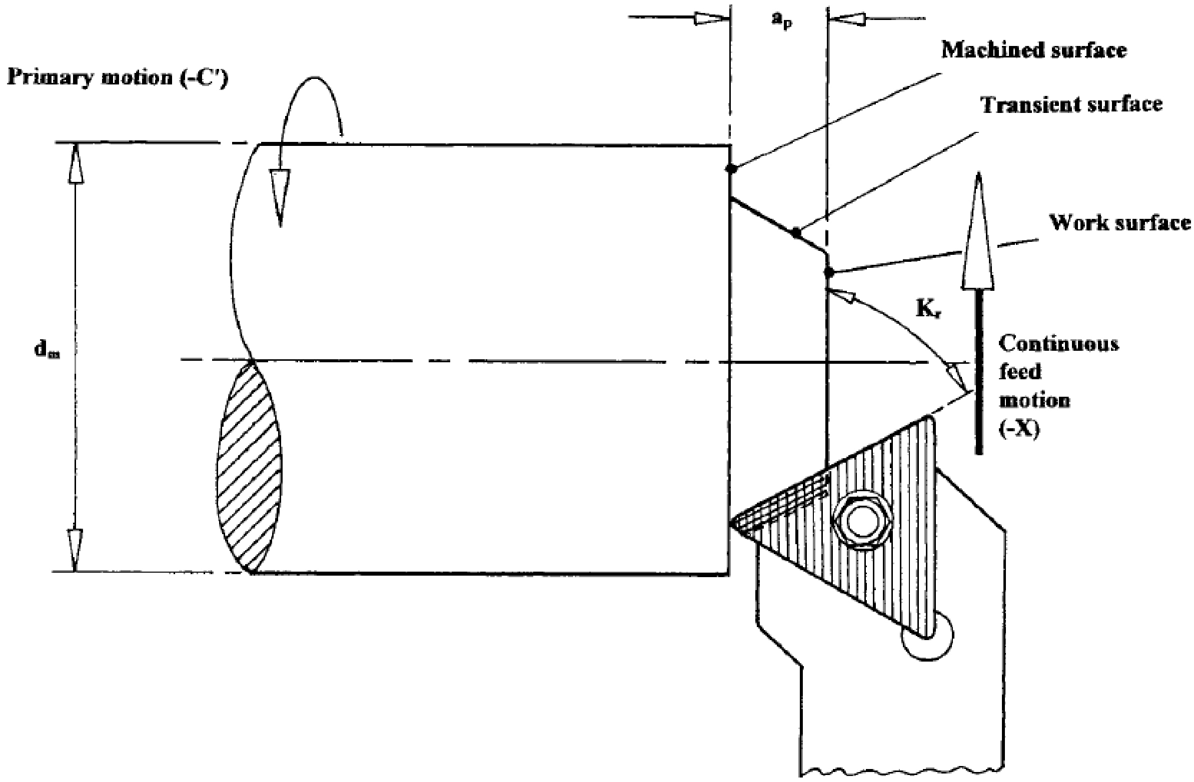


Figure 1.1.2.2 Facing operation [21].

Where abbreviations have following meaning and units:

- K_r … major cutting edge angle [°] ,
- a_p … depth of cut [mm].

Main internal turning operations are:

- drilling,
- boring,
- reaming,
- tapping.

1.1.2.1 Generalities during turning

Basic relations for turning are listed in the following table.

Table 1.1.2.1 General relations for turning accordingly to [19].

Characteristic	Symbol	Equation	units
Frequency of rotation	N	$N = \frac{v_c \cdot 1000}{\pi \cdot D}$	1/min
Cutting speed	v_c	$v_c = \frac{N \cdot \pi \cdot D}{1000}$	m/min
Cutting power	P_c	$P_c = \frac{v_c \cdot f \cdot a_p}{60\,000 \cdot \eta}$	kW
Power consumed by machine engine	P_{mc}	$P_{mc} = \frac{P_c}{\eta}$	kW
Specific cutting coefficient (Specified cutting pressure)	k_c	$k_c = \frac{1 - 0{,}01 \cdot \gamma_0}{h^{mc}}$	N/mm^2
Chip thickness	h	$h = f \cdot \sin(К_r)$	mm
Chip section	A_D	$A_D = f \cdot a_p$	mm^2
Material removal rate	Q or MMR	$Q = v_c \cdot f \cdot a_p$	cm^3/min

Specific cutting coefficient is an interesting coefficient that quantifies the effort necessary to execute cutting. Specific cutting coefficient is a function of material, cutting angles and cutting conditions.

Cutting forces during turning are displayed in the figure below.

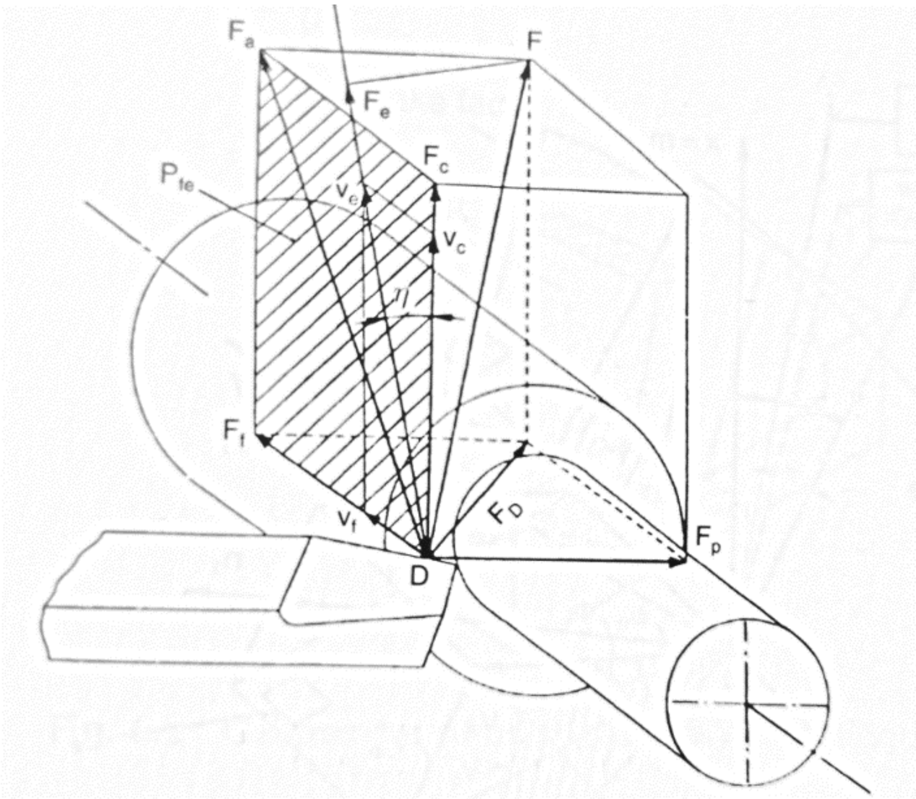


Figure 1.1.2.3 Cutting forces during turning [22].

Where:

- F_f … feed component of the resulting force [N],
- F_C …cutting component of the resulting force [N],
- F_e … resulting force [N],
- F_a … axial force [N],
- F_r … radial force [N],
- F_t … tangent force [N].

1.1.3 Milling

Milling is a machining process where the cutting tool performs a rotational movement and the chip is forcefully segmented. Cutting tool can have one or multiple cutting edges.

Typical milling operations are visualised in the following figure:

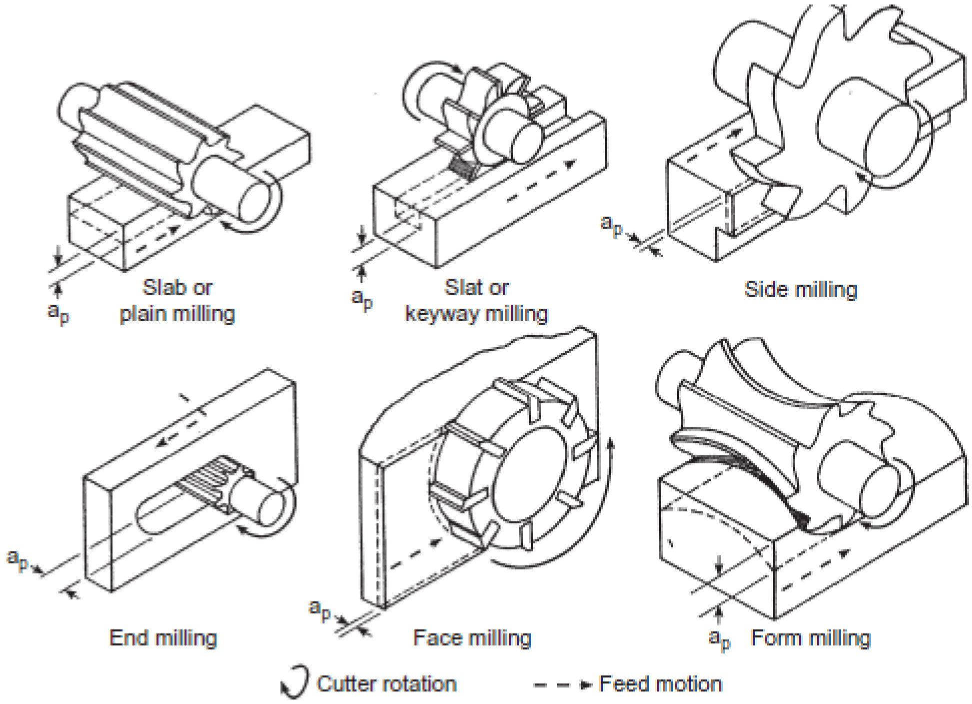


Figure 1.1.3.1 Typical milling operations [23].

Three types of milling can be differentiated based on which part of the tool is cutting [19]:

- face milling,
- end milling,
- combined with predominance.

In case of face milling, the workpiece surface is machined by the tip surface of the tool. On the other hand, in case of end milling the lateral surface of the tool is cutting. Combined milling refers to milling when the workpiece surfaces are machined by both lateral surface and the tip surface of the cutter are cutting while either face milling or end milling is predominant [19].

Modes of milling are differentiated based on the entry of the tool into the material while cutting:

- conventional milling (also called up milling),
- climb milling.

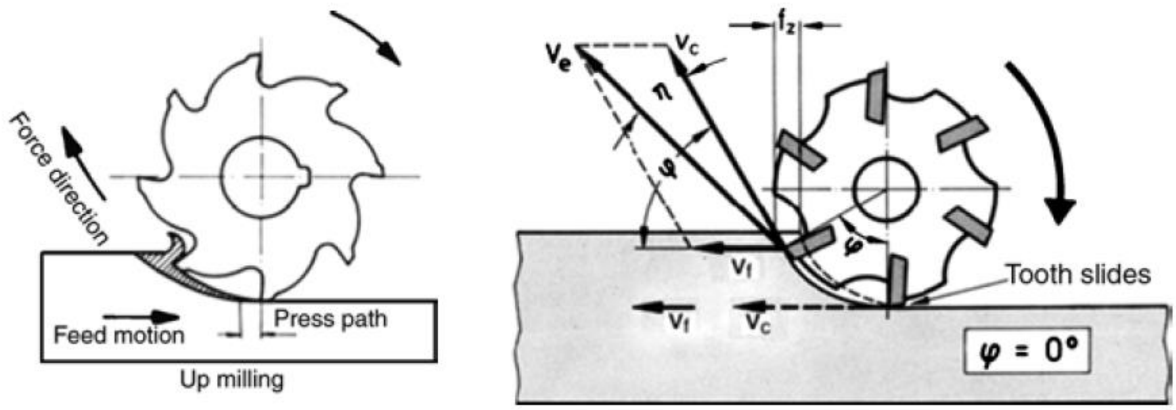


Figure 1.1.3.2 Conventional milling (up milling) [17].

Where:

- f_z … feed per flute,
- v_c … cutting speed,
- v_f … feed speed,
- v_e… resulting speed.

During climb milling the workpiece feed has the same direction as the force direction of the milling cutter. The chip cross section varies from maximum value to minimum value as is displayed in the following figure.

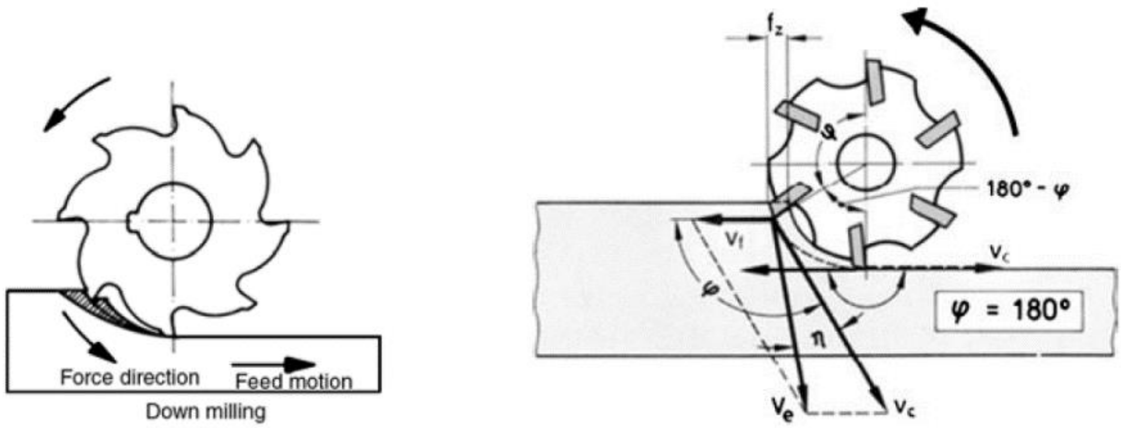


Figure 1.1.3.3 Climb milling [17].

1.1.4 Drilling

Drilling is a cutting process during which holes are created or enlarged by a rotating cutting tool. Drilling can be performed on a drill, a lathe or a mill.

Typical drilling operations are visualised in the following figure:

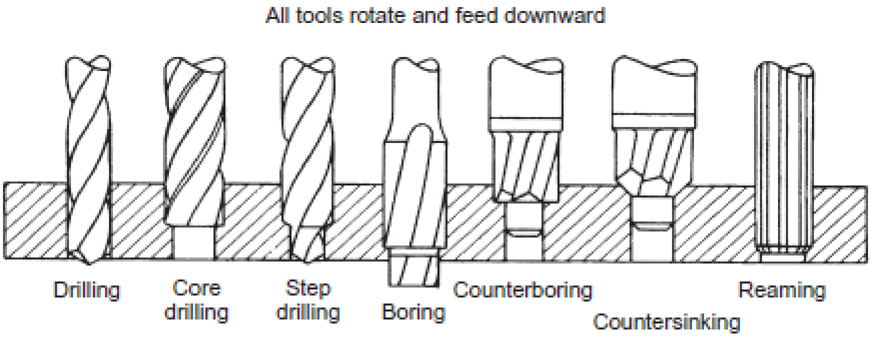


Figure 1.1.4.1 Some of typical drilling operations [23] .

1.1.5 Advanced machining strategies

Special machining strategies were elaborated during the case study. These chosen advanced techniques are:

- vibration assisted drilling,
- trochoidal milling strategy,
- plunge milling strategy.

1.1.5.1 Vibration assisted drilling

Vibration assisted drilling is a relatively new technology. It consists of adding axial vibration of high frequency to the drilling tool. This breaks more easily the chips and improves tool life because it significantly lowers tool wear due to thermic. Produced chips are fragmented and small and mechanical load are lower therefore the tool life is increased [24, 25].

For example the company Mitis offers special tool holders that add axial vibrations thanks to a mechanical component that generated vibrations when the spindle is spinning. Mitis drilling tool attachment is compatible with conventional drilling tools and is often employed in aeronautic industry, especially for drilling of composites [25, 26].

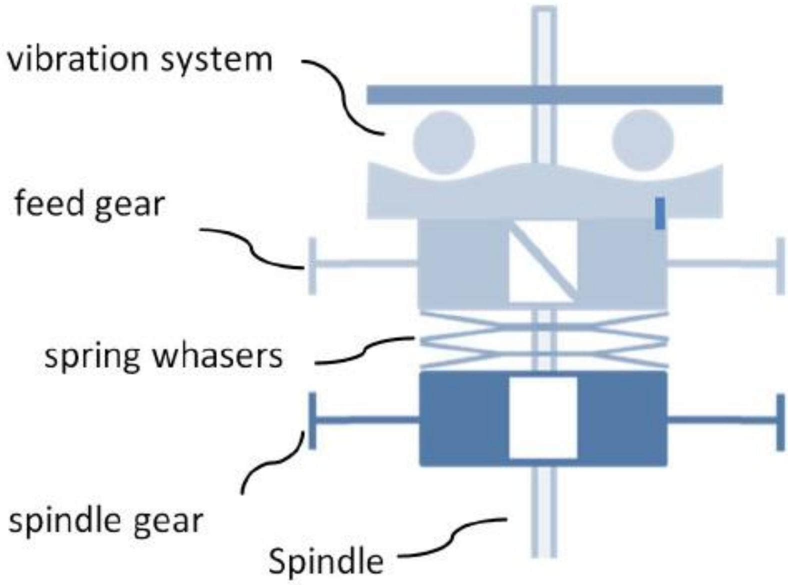


Figure 1.1.5.1 Vibration system attached to electrical drilling unit [24].

Chip morphology obtained using vibration drilling compared to normal drilling is shown on an example in the following figure.

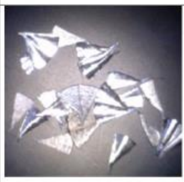
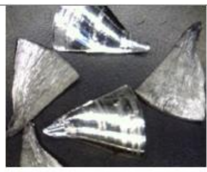
	N : 2000 rev/min **Feed rate : 0.04 mm**	**N : 2000 rev/min** **Feed rate : 0.20 mm**
Non-vibration		
Vibration	 Thickness: 0.111 mm Angular sector: 30°	 Thickness: 0.230 mm Angular sector: 45°

Figure 1.1.5.2 Example of chips obtained using vibration drilling attachment [24].

This technology has a disadvantage in industrial context - the initial investment needed. Products commercially available are quite expensive, even though the increased tool life eventually returns the initial investment.

1.1.5.2 Trochoidal milling

Trochoid is a family of curves and a type a cycloid (locus of a point at a distance from a circle rolling around a straight line) [11, 12].

Trochoid can be described by the following parametric equation [11]:

$$\begin{cases} x = a \cdot \theta - b \cdot sin\theta \\ y = a - b \cdot cos\theta \end{cases} \quad (1)$$

Where:

- b… distance from the centre of the circle,
- a… radius of the cercle.

Example of a trochoidal can be seen in the following figure.

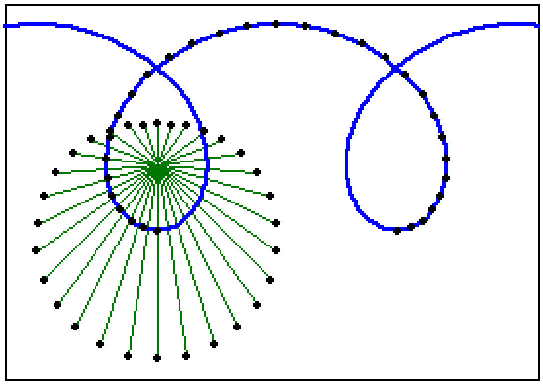


Figure 1.1.5.3 Trochoidal curve [11].

During trochoidal milling the feed motion is in direction of the trochoidal trajectory.

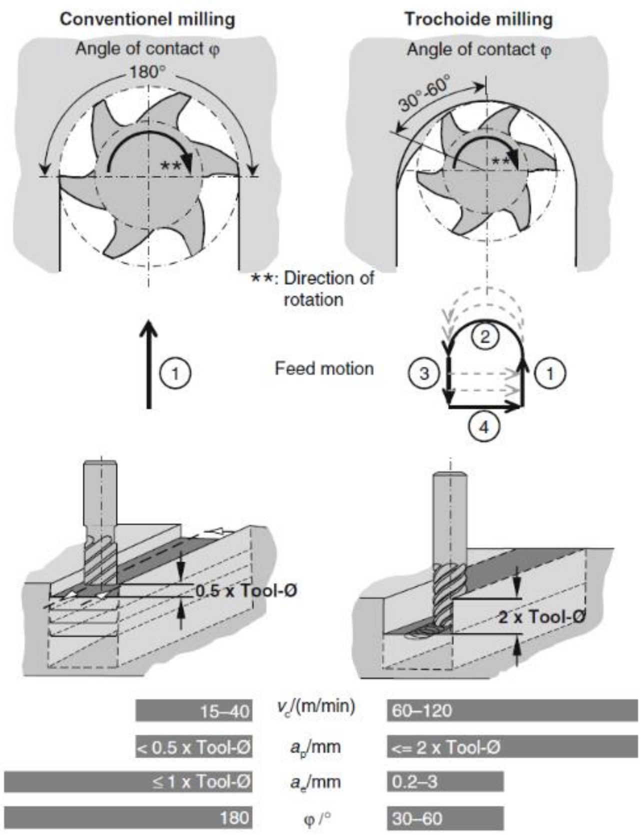


Figure 1.1.5.4 Conventional milling compared to trochoidal milling [27].

For trochoidal milling, the location of the centre point can be described with parametric equation [28]:

$$x = R_p \cdot sin\theta + \frac{(S_{tr}\theta)}{2\pi}$$
$$y = R_p \cdot cos\theta \qquad (2)$$

Where:

- R_p … radius of planetary revolution,
- S_{tr}… stepover at every planetary revolution,
- θ … angle defining the position of the cutter.

In industrial contexts especially for rouging strategies it is needed to eliminate large volumes of material in reduced machining times. Optimizing tool path through trochoid milling can meet such demands because it is a continuous trajectory. Trochoid milling is a strategy implementing trochoidal movement. This trajectory eliminates accelerations and decelerations, therefore the tool movement has constant speed [13].

Trochoidal milling is highly effective even for hardened materials [14].

Two types of trochoid milling can be differentiated:

- circular trochoidal milling,
- true trochoidal milling.

The difference between circular and true trochoidal milling is displayed on the figure below.

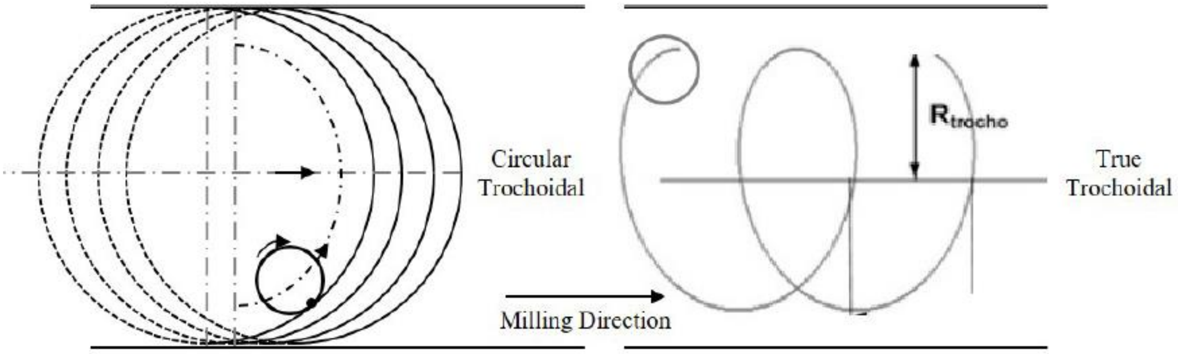


Figure 1.1.5.5 Circular trochoidal milling trajectory (left) and true trochoidal milling trajectory (right) [29].

Circular trochoidal milling is further detailed in the figure below.

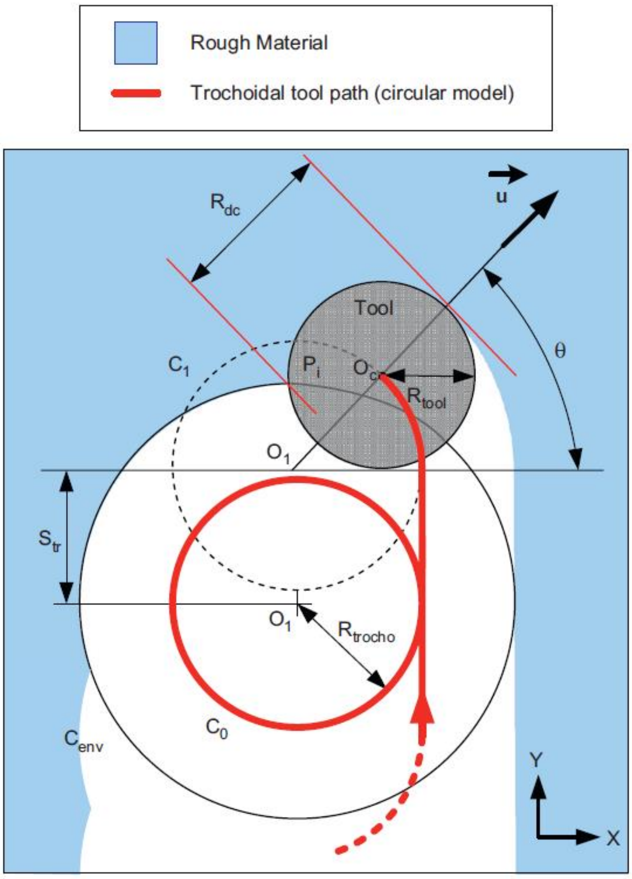


Figure 1.1.5.6 Circular trochoidal milling trajectory [13].

Trochoidal milling and conventional groove milling are compared in the following table.

Table 1.1.5.1 Comparison of conventional and trochoidal milling for groove machining accordingly to [19].

Parameter	Symbol	Conventional milling	Trochoidal milling
cutting speed	v_c	low	high
radial depth of cut	a_e	maximum value of ae possible is recommended, a_e = tool diameter	5-10% of cutting diameter recommended
axial depth of cut	a_p	little recommended	important recommended
number of teeth (number of flutes)	Z	fewer Z recommended	not limited
chips	-	Difficult chip evacuation, of large dimensions	Thin, easy to evacuate
power	P_c	High	Low
tool wear	-	at the tip of the tool	on the whole cutting part of the tool
machine requirements	-	Rigid	CNC, modern
coolant	-	-	Compressed air or spray-mist recommended

Typical trochoidal trajectory is represented in the figure below.

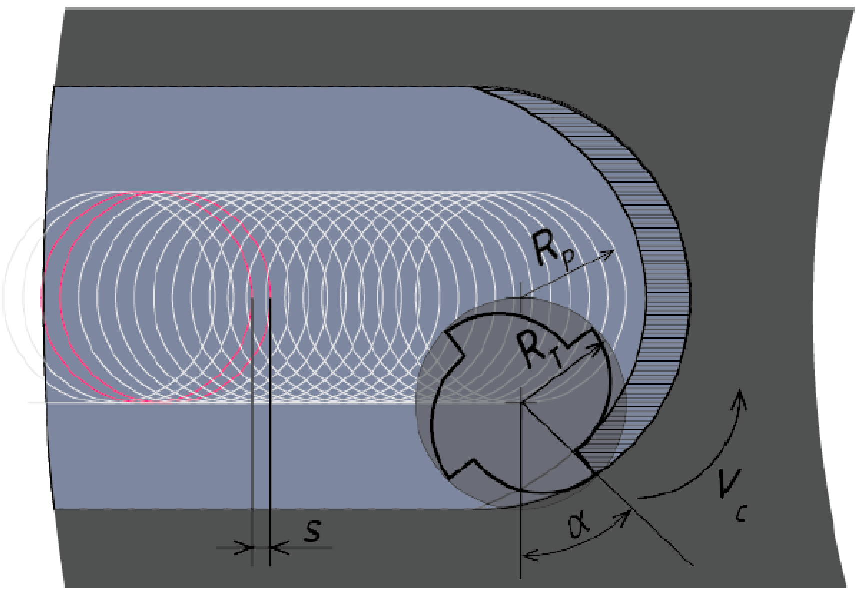


Figure 1.1.5.7 Trochoidal tool path [30].

Trochoidal trajectory can be 3D as well, as shown on representation of plunge trochoidal milling in the figure below.

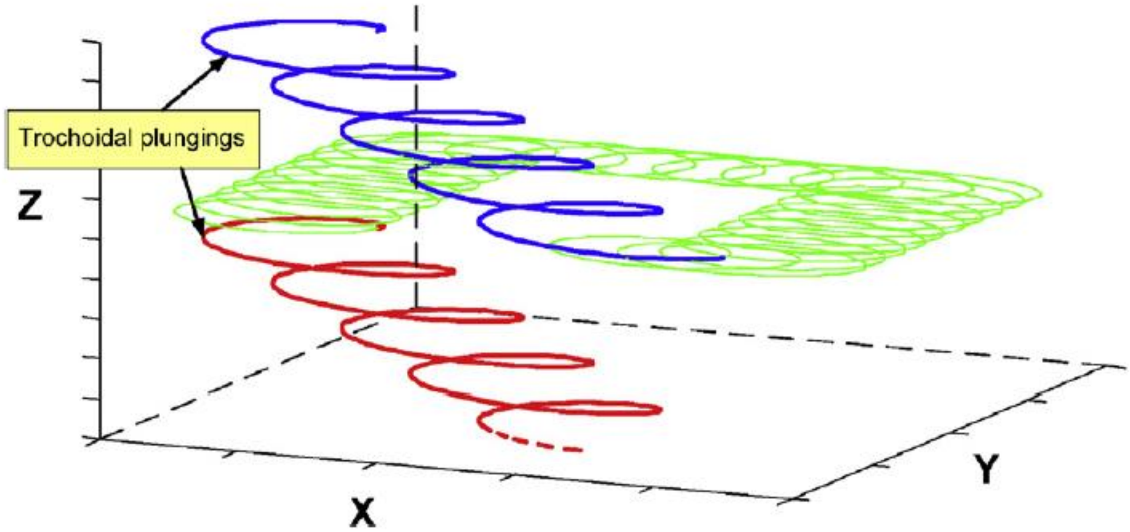


Figure 1.1.5.8 Trochoidal plunging trajectory [13].

1.1.5.3 Plunge milling

While trochoidal milling uses large radial depth of cut while axial depth of cut is small, plunge milling uses an opposite approach. During plunge milling the axial depth of cut is more important than radial depth of cut.

Plunge milling is a milling strategy most used for roughing, where the feed movement is in the same direction as the axis of the rotating tool [3].

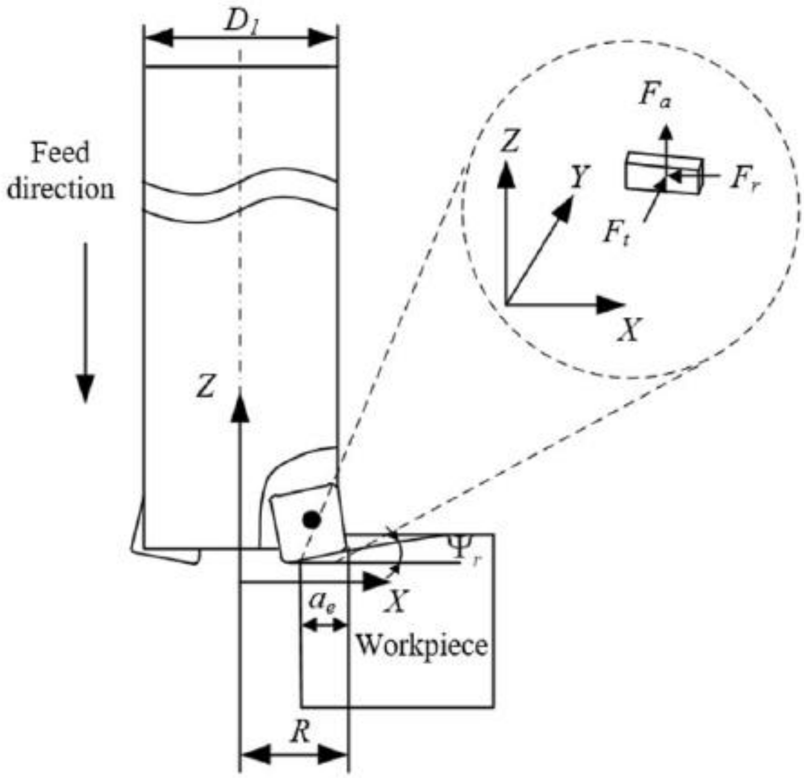


Figure 1.1.5.9 Plunge milling principle [31].

During plunge milling very deep and narrow passes in the material are often machined.

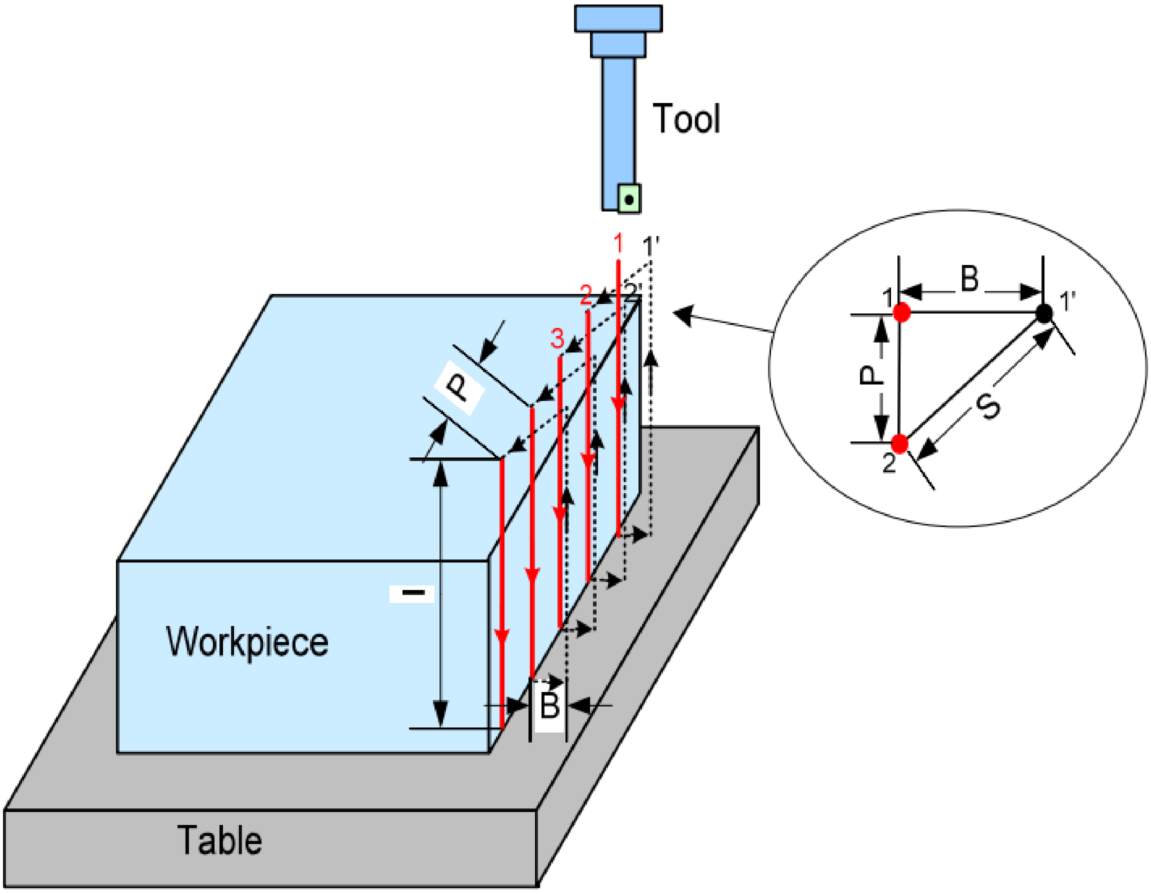


Figure 1.1.5.10 Typical tool trajectories during plunge milling.

The walls after roughing using plunge milling are not straight and finishing is needed [3].

1.2 CHIP FORMATION

The machining process is one of the most complex fabrication processes [3].

There are many factors influencing the chip formation, for example following factors [3]:

- cutting forces,
- temperature,
- tool wear,
- friction,
- cutting power,
- surface integrity.

Chip is mostly formed by the main cutting edge and the nose, even though a small part of the secondary cutting edge contributes also to the chip formation process. To simplify the study of the chip formation, only the action of the cutting edge is considered. This simplified case is called orthogonal cutting [32].

During orthogonal cutting,

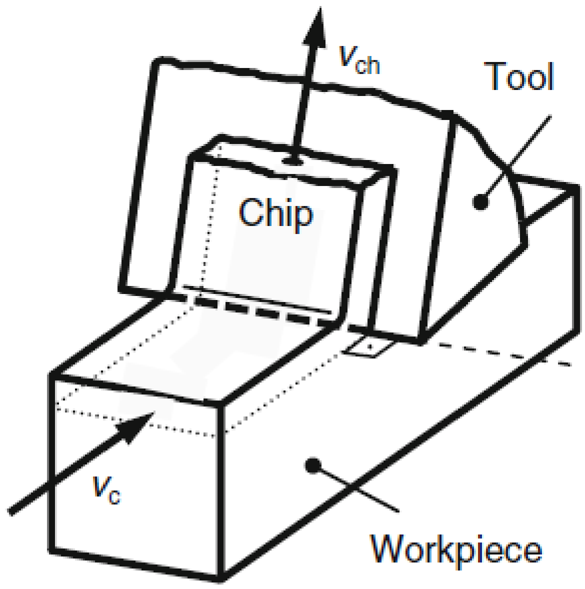


Figure 1.1.5.1 Free orthogonal cutting [27].

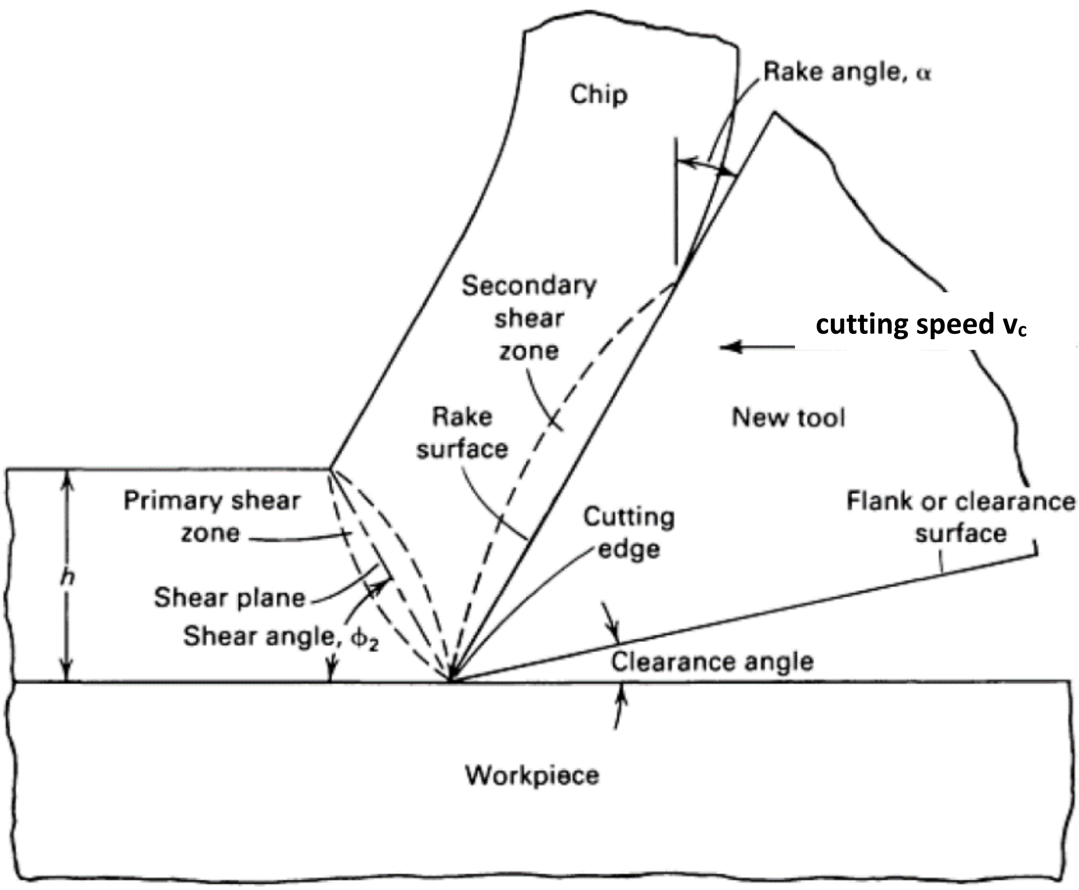


Figure 1.1.5.2 Relations between chip, workpiece and tool [10].

1.3 CHIP CONTROL

Chips can be classified accordingly by their form as:

- continuous chips,
- segmental chips (elemental chips),
- shear localised chips,
- discontinuous chips [3].

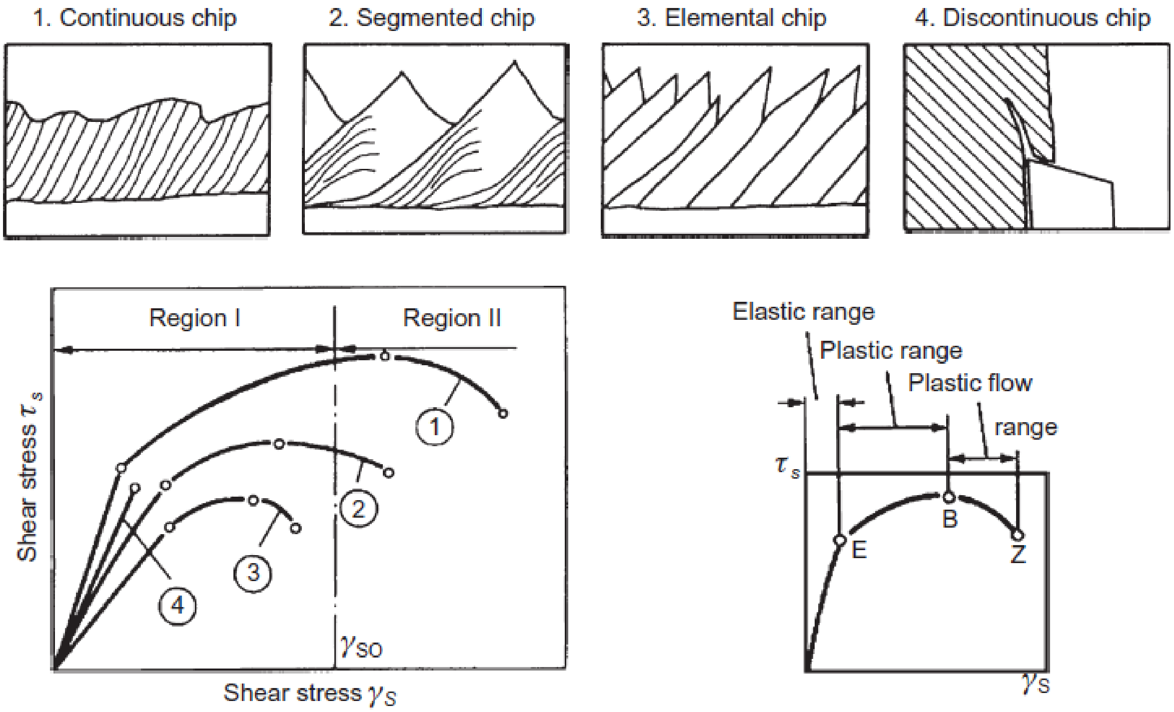


Figure 1.2.1 Chip type with corresponding shear stress regions [22].

Continuous chips are long and not fragmented. Continuous chips are formed only during machining operations with continuous cutting and constant chip thickness, the best example is turning, but continuous chips are observable also during drilling or thread tapping. [3]

Chip fragmentation is desired because [10]:

- continuous chips are dangerous for humans in proximity of the machine,
- continuous chips can damage the machined surface,
- continuous chips can damage the machinery
- fragmented chips are more easily stored,
- fragmented chip are more easily evacuated by the cooling and lubrification fluid and allows flow of cooling and lubrification fluid to the tool increasing the tool life.

Segmental and discontinuous chips are acceptable.

Chip classification and formation due to stress/strain is visualized in the following figure.

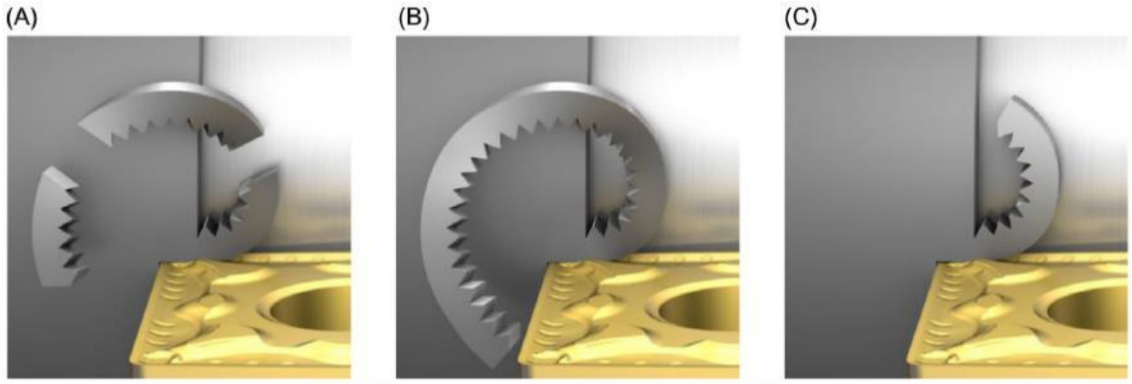


Figure 1.1.5.2 Chip breaking principles A) self-breaking, B) contacting with cutting inert, C) contact with workpiece [33].

There are many factors influencing chip breaking. They are categorised in the figure below.

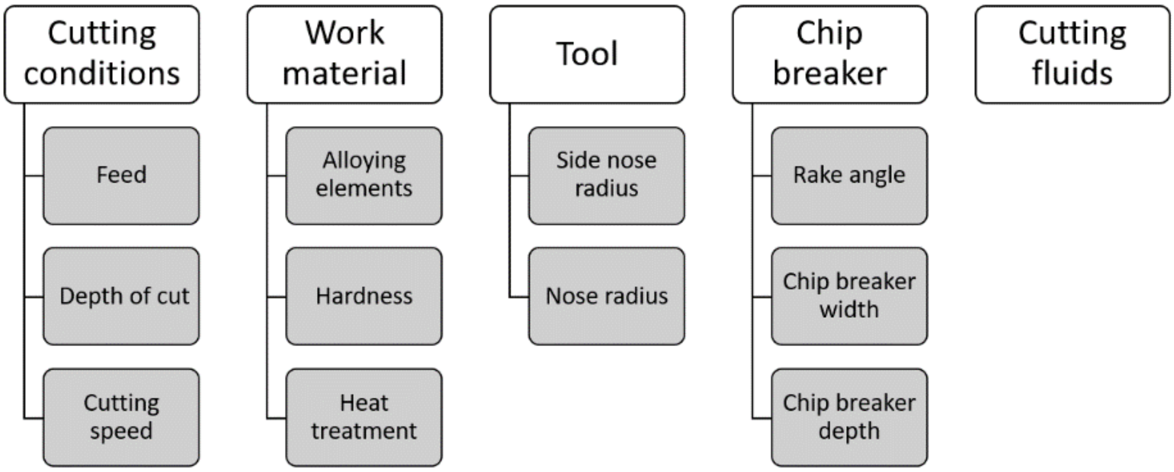


Figure 1.1.5.3 Parameters influencing chip breaking accordingly to [22].

Cutting conditions have key influence on chip breaking. The feed influences the chip breaking the most and is proportionate to the chip thickness. Depth of cut is proportionate to chip width. Effective range of the cutting tool is narrower with increasing cutting speed. Chip thickness decreases with increasing cutting speed [22].

Work material influences the thickness and curling of the chips. Harder steel produces much more curlier chips but thinner [22].

Tools with smaller nose radiuses are preferred for finishing operations while larger radiuses are preferred for roughing operations.

Chip breakers can be clamped or integrated on the face of cutting insert. Geometry of chip breakers changes their application, narrow and deep chip breakers usually perform better at lower feeds [22, 34].

Cooling and lubrification fluids (CLF) have positive influence on chip breaking and aid chip evacuation.

1.3.1 Normalised chip classification

Normalized chip classification is listed in the figure below.

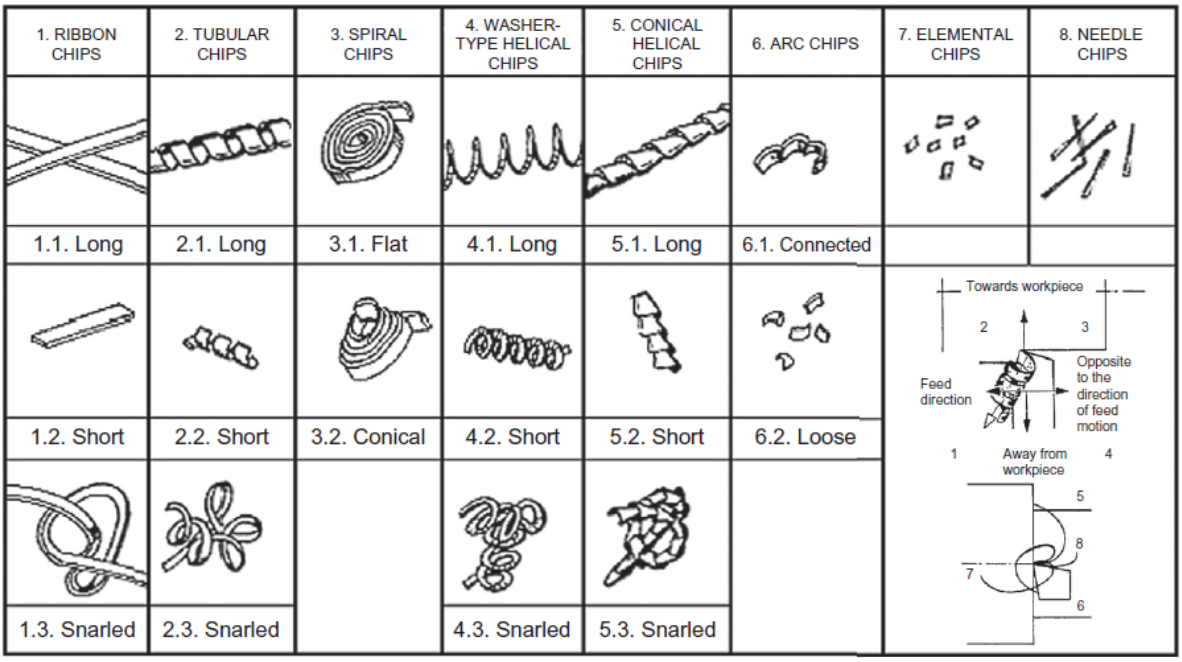


Figure 1.3.1.1 Normalised chip classification by ISO 3685-1977 (E) [22].

1.3.2 Chip control during turning

Cutting parameters influencing chip fragmentation the most during turning are:

- Depth of cut,
- Feed,
- Cutting speed,
- Lubrification
- Chip breaker on the cutting insert.

It should be noted that the influence of feed is more of an influence of chip thickness h_c, That is why at same feed but different angle K_r the chip fragmentation will be different.

In turning, chip thickness h_c can be calculated with the following equation:

$$h_c = f \cdot sin K_r \quad (3)$$

1.3.3 Chip control during milling

As a general rule, the chips during milling are forcefully fragmented. The chip fragmentation is given by the discontinuous nature of milling – flutes engage and disengage in the material cutting as they are rotated. This forces the chips to break.

Cutting parameters influencing chip fragmentation the most during milling are:

- Axial depth of cut
- Radial depth of cut,
- Tool rotation speed,
- Number of flutes of the tool,
- Feed per dent
- Chip breakers on the tool.

1.3.4 Chip control during drilling

Chip control during drilling can be problematic because the cutting process is continuous.

Chip peck cycles can be introduced in the NC program in effort to break the chip by pausing the infeed movement while keeping the tool rotating or even to retract the drilling tool after drilling to a certain depth predefined by user before re-engaging in drilling.

Another solution for long chips during drilling is vibration assisted drilling.

1.3.4.1 **Chip peck drilling**

Chip peck cycle G83 refers to drilling cycle that is consisted of drilling till programmed depth and then returning to the initial plane R before returning to drill further. The pecks of the drilling tool evacuate the chips and force them to break into smaller chips than during continuous drilling that often produces very long non-fragmentated chips. The chip peck cycle is used mainly for deep holes.

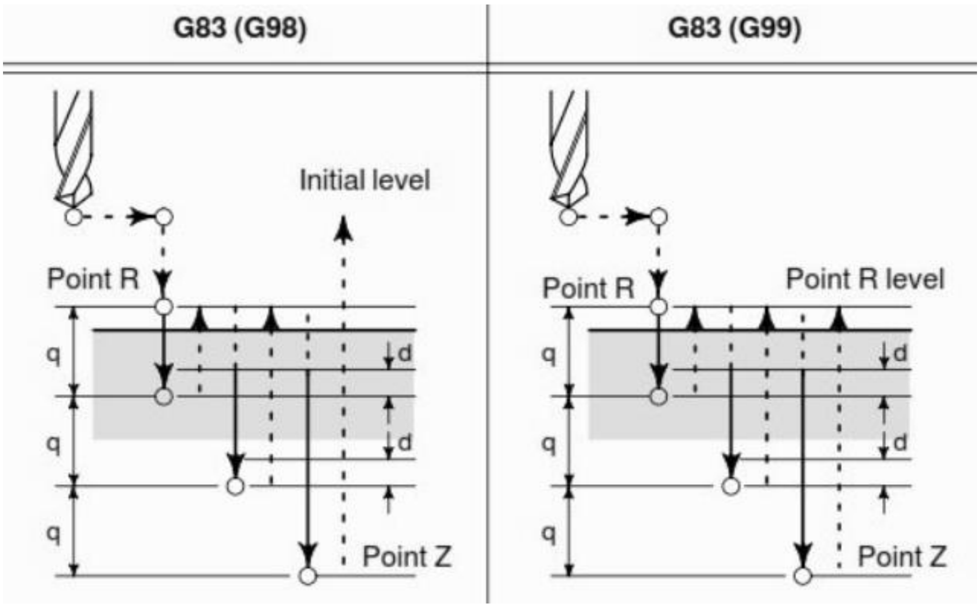


Figure 1.3.4.1 Chip peck drilling cycle for Fanuc control system [35].

The syntax for the chick peck cycle in Fanuc control system is:

G83 X_ Y_ Z_ R_ Q_ F_ K_ ;

Where:

- X Y – X and Y coordinated of the centre of the hole,
- Z – depth of the drilled hole (in Z axis),
- R – position of the r plane,
- q – depth of peck,
- F – Cutting federate,
- K – Number of repeats.

Chip peck cycle G73 is a similar cycle but the tool does not exit the hole totally but only retracts by a certain distance and stays without feed motion for programmed dwell time.

Chip peck cycles result in better chip evacuation but more important machining times.

1.3.4.2 Vibration assisted drilling

Vibration assisted drilling is an advanced technique for chip control during drilling [36].

Vibration assisted drilling was presented in chapter Advanced machining strategies.

Vibration assisted drilling results in excellent chip fragmentation while keeping the machining time almost unchanged and also promotes longer tool life.

1.4 CNC MACHINING

The abbreviation CNC stands for the term Computer Numerical Control. CNC machining is different from conventional machining because the tool-workpiece movement is controlled numerically by a computer. While conventional machining is controlled manually, CNC machining automates partially or entirely. Computer numerical control represents an automation of machine tools [3].

Structure of the CNC machine is similar to structure conventional machines but generally is more complex. In addition to the structure of a conventional machine, a CNC machine also contains complex systems of movement control and a multitude of sensors (detectors). The movements are usually controlled by servomotors that are capable of precise movements.

1.4.1 Creation of NC program

CNC programs are often generated using the CAD/CAM technology.

3D model of the machined component is created in Computer Aided Design. The 3D model is then imported in a Computer Aided Manufacturing software that allow creation of tool paths and simulate cutting. To obtain a NC program, the CAM uses postprocessor that translate the created tool paths to ISO programming language that is readable by the CNC machine [3].

Sometimes virtual machining is then used to simulate the machining on a virtual replica of the NC machine and machine-tool system. Virtual machining can be used to simulate cutting forces or find collisions [37].

1.4.2 Structure of a NC program

The structure of NC programs uses a programming language and syntax specific to the control system of the machine. Most of control systems use G programming language that has many varieties but the most commonly used one is the ISO programming language. Every command is composed of a letter address and its numerical value. For better orientation in the programs, blocks (lines) are assigned a block line number consisting of letter address N and number of the block but block numbers are not necessary for the functioning of the program. Blocks contain commands and are executed consecutively in numerical order. The letter address can be any letter of the alphabet but the most used are G and M functions. In Sinumerik control systems G functions are also called preparatory functions and M functions can also be called auxiliary or Miscellaneous functions. The functions and their application may vary for turning and for milling.

1.4.2.1 Letter addresses

Table 1.4.2.1 Most used letter addresses in ISO G-code [38].

A, B, C	Absolute/incremental position in corresponding rotational axis: A, B
G	Preparatory function
F	Feed rate designation
M	Miscellaneous (auxiliary) function
N	Block number
S	Spindle speed
T	Tool selection
U, V, W	Incremental position in corresponding linear axis: X, Y or Z (Fanuc)
X, Y Z	Absolute or incremental position in corresponding linear axis: X, Y or

1.4.2.2 G function in FANUC programming language

Often used G functions for in FANUC programming language are listed below.

Table 1.4.2.2 G functions is FANUC programming language [38].

G00	Rapid traverse
G01	Linear interpolation
G02	Clockwise (CW) circular interpolation
G03	Counterclocwise (CCW) circular interpolation
G04	Dwell time preset
G09	Exact stopping before continuing to the next block, diminution of
G17	X/Y plane selection for linear and circular interpolation
G18	X/Z plane selection for linear and circular interpolation
G19	Y/Z plane selection for linear and circular interpolation
G20	Data entry in imperial system (inch)
G21	Data entry in the Metric System (mm)
G28	Return to reference position

G29	Zero point return
G33	Threading with constant lead
G35	Circular threading CW
G36	Circular threading CCW
G40	No tool radius compensation
G41	Tool radius compensation left of the workpiece contour
G42	Tool radius compensation right of the workpiece contour
G53	Frame suppression (in concerned block)
G54	First settable zero offset
G55	Second settable zero offset
G56	Third settable zero offset
G57	Fourth settable zero offset
G70	Input in inches
G71	Input in metric system
G73	Chip peck cycle for deep holes at high speed
G74	Approaching reference point
G75	Approaching fixed point
G83	Chip peck cycle
G90	Absolute dimension input
G91	Incremental dimension input
G93	Inverse time federate coding
G94	Linear feed rate Fv in mm/min or inch/min
G95	Revolution feed rate Fv in mm/revolution or inch/revolution
G96	Constant velocity on
G97	Constant velocity off

1.4.2.3 **Most commonly used M functions**

Table 1.4.2.3 M function if ISO programming language [19].

M00	Programmed stop
M01	Optional stop
M02	Program end and return to program beginning
M03	Spindle turning clockwise (CW)
M04	Spindle turning counterclockwise (CCW).
M05	Spindle stop
M06	Tool change
M17	Subprogram end
M30	Subprogram's end, return to the beginning of the program

1.5 WORKPIECE MATERIALS

Many materials can be machined. Materials that were machined varied in history.

Historically, the first machined materials were naturally occurring materials like bone, wood, or stone. With the increasing knowledge of mankind, metal processing became known. Metals became an important and valuable material.

Another modern groups of materials that can be machined are plastics and composites.

Metals represent the most machined group of materials to this day [22].

1.5.1 Metal material groups

Metals are rarely used in pure composition, on the contrary most of them are alloys [39].

Commonly machined metal materials are [22]:

- copper and its alloys,
- carbon steels,
- alloyed steels,
- stainless steels,
- cast irons,
- titanium and its alloys,
- nickel based alloys,
- refractory metals,
- light materials: Al and its alloys, Mg an its alloys.

International Organization of Standardization regroups metalworking workpiece materials to multiple categories.

There are six main ISO cutting inserts material groups:

- group P – steel,
- group M – stainless steel,
- group K – cast iron,
- group N – non-ferrous materials,
- group S – superalloys,
- group H – hardened materials.

ISO material groups also have colour distinction that is used in tool catalogues and on packaging of cutting tools as shown in the figure below.

P	Non-alloy steel and cast steel Low-alloy steel and cast steel High-alloy steel and cast steel Stainless steel and cast steel (ferritic/martensitic)
M	Stainless steel (austenitic)
K	Gey cast iron Ductile cast iron Nodular cast iron (ferritic/perlitic)
N	Non-ferrous metals Aluminium and aluminium alloys
S	Superalloys Titanium and titanium alloys
H	Hard cast iron Hardened steel

Figure 1.5.1.1 Metalworking workpiece ISO cutting inserts material groups [40].

ISO material groups can be further divided into subgroups. As a general rule, the higher the number following the material group letter, the harder the material is to machine.

ISO	MC	Material
P	P1	Unalloyed steel
	P2	Low-alloyed steel (≤5% alloying elements)
	P3	High-alloyed steel (<5% alloying elements)
	P4	Sintered steels

ISO	MC	Material
M	P5	Ferritic/Martensitic stainless steel
	M1	Austenitic stainless steels
	M2	Super-austenitic, Ni≥20%
	M3	Duplex (austenitic/ferritic)

ISO	MC	Material
K	K1	Malleable cast iron
	K2	Gray cast iron
	K3	Nodular SG iron
	K4	CGI
	K5	ADI

ISO	MC	Material
N	N1	Aluminium-based alloys
	N2	Magnesium-based alloys
	N3	Copper-based alloys
	N4	Zinc-based alloys

ISO	MC	Material
S	S1	Iron-based alloys
	S2	Nickel-based alloys
	S3	Cobalt-based alloys
	S4	Titanium-based alloys
	S5	Tungsten-based alloys
	S6	Molybdenum-based alloys

ISO	MC	Material
H	H1	Steel (extra hard)
	H2	Chilled cast iron
	H3	Stellites
	H4	Ferro-TiC

Figure 1.5.1.2 ISO material subgroups [22].

Specific cutting pressure k_c [N/mm^2] range varies for each ISO material group as follows:

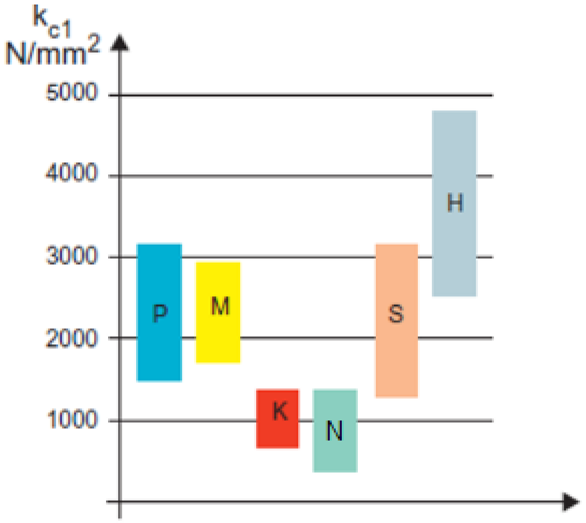


Figure 1.5.1.3 Approximate ranges of specific cutting pressure for ISO material groups [22].

1.5.2 Proprieties

Proprieties of materials are the key factor for choosing of the workpiece material for a component.

Mechanical proprieties are for example [39]:

- Toughness,
- Hardness,
- Yield Strength (limit of elasticity),
- Ductility
- Tenacity.

Other material proprieties are for example:

- Resistance to corrosion,
- Weldability.

For machining, especially important material proprieties are:

- Hardness,
- Ductility.

Workpiece material must be always less hard than the material of the cutting tool.

Ductile material while usually lower in hardness cause difficulties in machining because the material can stick to the cutting edge and cause a built-up edge.

Weldability is a complex propriety of steels. Because of its complexity it usually isn't a specifically guaranteed propriety. Nevertheless, the manufacturers of steel usually give necessary information for good welded joint realisation [39].

Carbon equivalent can be used to evaluate weldability of steels. It is an empirical rule. It is used to estimate the quantity of martensite structure. Too much of a martensite structure has negative influence on weldability because it can cause cold fractures of the welded joint [39].

Chemical composition of metal material has influence on proprieties and structure of the metal or metallic alloy. Steels can have a wide variation in proprieties based on their chemical composition a percentage of alloying elements.

Influence of alloying elements on material proprieties for steels is listed in the table below [6].

Table 1.5.2.1 Influence of alloying elements on material proprieties of steels [6].

Alloying element	Influence
Aluminium	deoxidant; slight increase in quench ability; alloying element for steel for nitridation
Boron	increases quenching ability of low carbon steels
Chrome	increase in resistance to corrosion and to oxidation
Cobalt	increases hardness of ferritic structure at elevated temperatures
Manganese	neutralises fragility cause by presence of sulphur; significantly increases the quench ability
Molybdenum	significantly increases the quench ability; favourites small grain structure; increases hardness at elevated temperatures; increases resistance to abrasion; increases resistance to corrosion of stainless steels
Nickel	Increases strength of non-tempered steels; increases toughness of steels with ferrite-perlite structure; favourites formation of austenitic structure
Phosphor	Increases toughness of low carbon steels
Plomb	Increases machinability (in 0,15-0,35wt%)
Silicon	deoxidant, decreases magnetism of steels; increases toughness of low alloy steels ; increases quenching ability of steles without traces of graphite
Sulphur	considered as impurity; increases tendency of fracture occurrence
Tungsten	creates hard precipitations significantly resistant to abrasion; increases hardness; increases toughness at high temperatures
Vanadium	favourites fine grains structures; increases quenching ability

1.5.3 Metal phase diagrams

As mentioned earlier metals are rarely used in the industry are rarely in their pure form. In most cases metal material used in the industry are metal alloys [39].

Metal phase diagrams show phases for material of certain percentage of alloying elements at certain temperature. A phase is region or regions of an alloy that is characterised by a composition and an identic structure [39].

The most used are binary metal phase diagrams. Binary diagrams have two main chemical components and the diagrams are therefore 2D, because they have only two axis: temperature and percentage of mass composition of one of the two components [39].

Phases present in binary metal phase diagram of iron and cementite are described in the following table.

Table 1.5.3.1 Metal phases of Fe-Fe_3C [41].

Phase (microconstituent)	**Crystal structure of phases**	**Characteristics**
Ferrite (α-iron)	bcc	Relatively soft low-temperature phase; stable equilibrium phase
δ-ferrite (δ-iron)	bcc	Isomorphous with α-iron; high-temperature phase; stable equilibrium phase
Austenite (γ-iron)	fcc	Relatively soft medium-temperature phase; stable equilibrium phase
Cementite (Fe_3C)	Complex orthorhombic	Hard metastable phase
Graphite	Hexagonal	Stable equilibrium phase
Pearlite		Metastable microconstituent; lamellar mixture of ferrite and cementite
Martensite	bct (supersaturated solution of carbon in ferrite)	Hard metastable phase; lath morphology when <0.6 wt% C; plate morphology when >1.0 wt% C and mixture of those in between
Bainite	. . .	Hard metastable microconstituent; nonlamellar mixture of ferrite and cementite on an extremely fine scale; upper bainite formed at higher temperatures has a feathery appearance; lower bainite formed at lower temperatures has an acicular appearance. The hardness of bainite increases with decreasing temperature of formation.

Metastable iron-cementite (Fe-Fe_3C) metal phase diagram is shown in the figure below.

It should be noted that ledeburite is not a phase but a mixture of austenite and cementite.

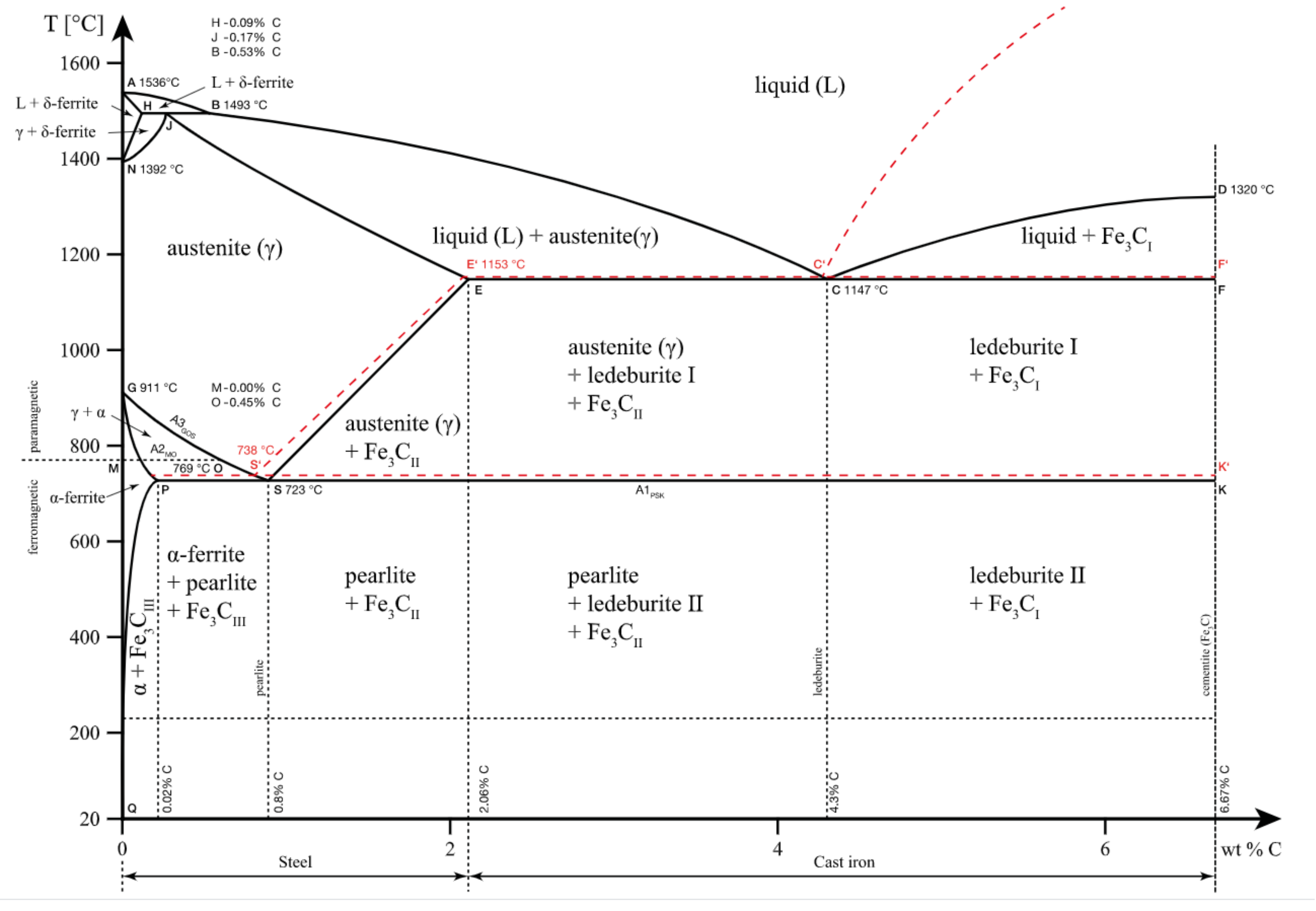


Figure 1.5.3.1 Metastable iron-cementite (Fe-Fe_3C) metal phase diagram [42].

1.5.4 Heat treatment of steels

Heat treatments serve to modify material proprieties by changing their microstructure.

Types of heat treatments of steels and their goal are listed in the table below

Table 1.5.4.1 Heat treatments of steel [6, 41].

Heat treatment	Goal of heat treatment		Principle
Quenching	increase of R_e and R_m increase of hardness decrease of K decrease of A%	Rapid cooling typically from 815-870°C, producing controlled amount of martensite	The steel is heated to a zone with austenitic structure and then quickly cooled. Quick cooling prevents austenite from transforming to ferrite nor perlite. Obtained solid solution is iron saturated and called martensite. Quenching is also called hardening.
Tempering	decrease of R_e and R_m decrease of hardness increase of K increase of A%	Heating just below austenitic temperature, at about 700°C, time at tempering temperature, cooling	Controlling grain size, modify toughness and ductility of previously quenched or normalized steels. Martensite is fragile after quenching, tempering is necessary to decrease its fragility
Annealing	softening of material, increasing ductility, increases machinability promotes dimension stability	Heating and holding at temperature above austenitic temperature, controlled slow cooling	Principle of annealing is inverse to that of quenching
Normalizing	increase of R_e and R_m homogenous structure with fine grains	Heating and holding temperature at 800-920°C, controlled slow cooling	Homogenous austenitic structure is obtained. recrystallization occurs

Hardened steels are usually harder to machine. Turning of hardened steels harder than 35 HRC is referred to as hard turning [43].

1.5.5 Machinability

Machinability is a material propriety that measures the ease or difficulty with which the material can be machined – shaped by cutting process. Machinability is not only connected to the material, but to the machining system too [44].

Machinability can be measured by many different criteria, for example [3]:

- tool life,
- cutting forces,
- control of acceptable forms of chips (for turning),
- surface integrity.

These criteria may be contradictory, material may have good machinability by one criteria and inconvenient by other criteria [3].

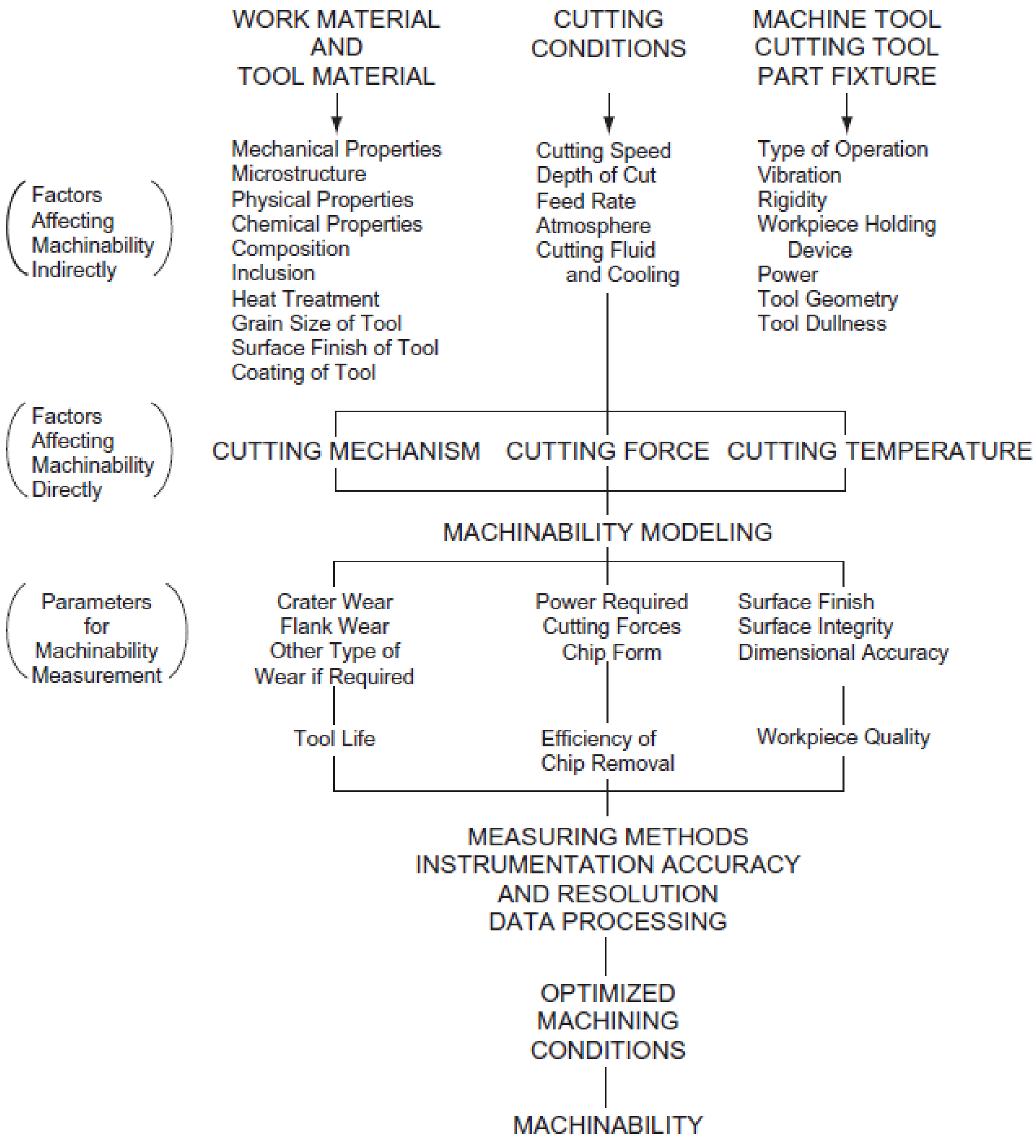


Figure 1.5.5.1 Factors influencing machinability of materials. [45]

1.5.5.1 **Nominal Machinability Rating**

Machinability of a material can be compared thanks to Nominal Machinability Rating (NMR) which serves as a comparison of material removal with material removal of a reference material. [46]

It can be expressed by following equation [46]:

$$NMR = \frac{\xi}{\xi_{ref}} \times 100 \tag{4}$$

Where the symbols have following meaning [46]:

- NMR … Nominal Machinability Rating,
- ξ …material removal rate,
- ξ_{ref} … material removal rate of reference material.

1.5.5.2 **Influences on machinability**

Possible causes of bad material machinability are regrouped on the following picture.

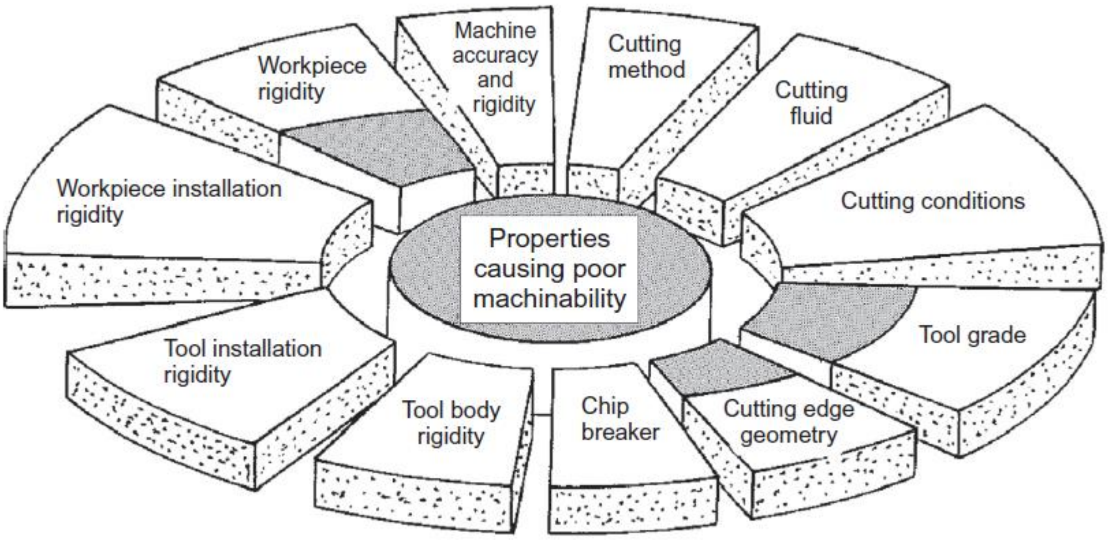


Figure 1.5.5.2 Causes of poor machinability [47].

1.5.5.3 Influence of hardness on machinability

Material proprieties affect the machinability of materials.

Harder materials require more power to be machined as is illustrated on the figure below.

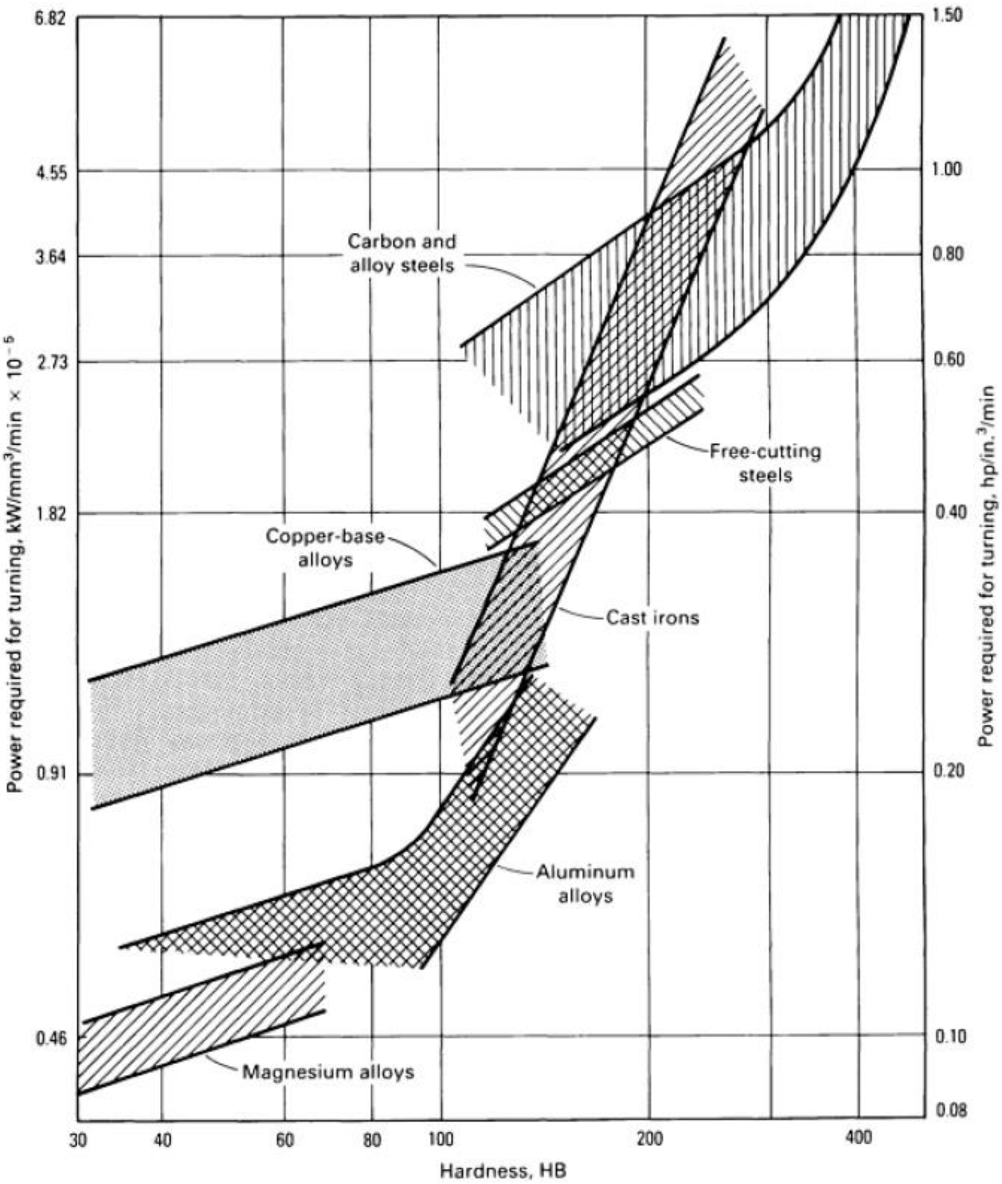


Figure 1.5.5.3 Influence of hardness on power required for turning [10].

Heat treated steels have generally higher hardness and therefore have worse machinability.

1.6 CUTTING TOOLS

1.6.1 Cutting tool materials

History of cutting materials starts with naturally occurring materials like flints, rock, wood or bone. Technically the oldest found cutting tools were from ceramic material – flints are naturally occurring ceramic material and stone-age people used chipped flits to cut hunting tool. When metal production became known, metals like copper and iron were used. With invention of steel production, most of cutting tools were from steel. Cutting tools went through the most major developments between 1900 and 1980 [18].

Today's cutting tools are from following materials:

- Plain carbon steels,
- High speed steels,
- Cemented carbide,
- Ceramic's and Cermet's.

Cemented carbides are one of the most used material group for cutting tools today.

The most employed cemented carbide tools are tungsten carbides. [21]

Overview of materials used for tools with defined cutting edge are listed in the figure below.

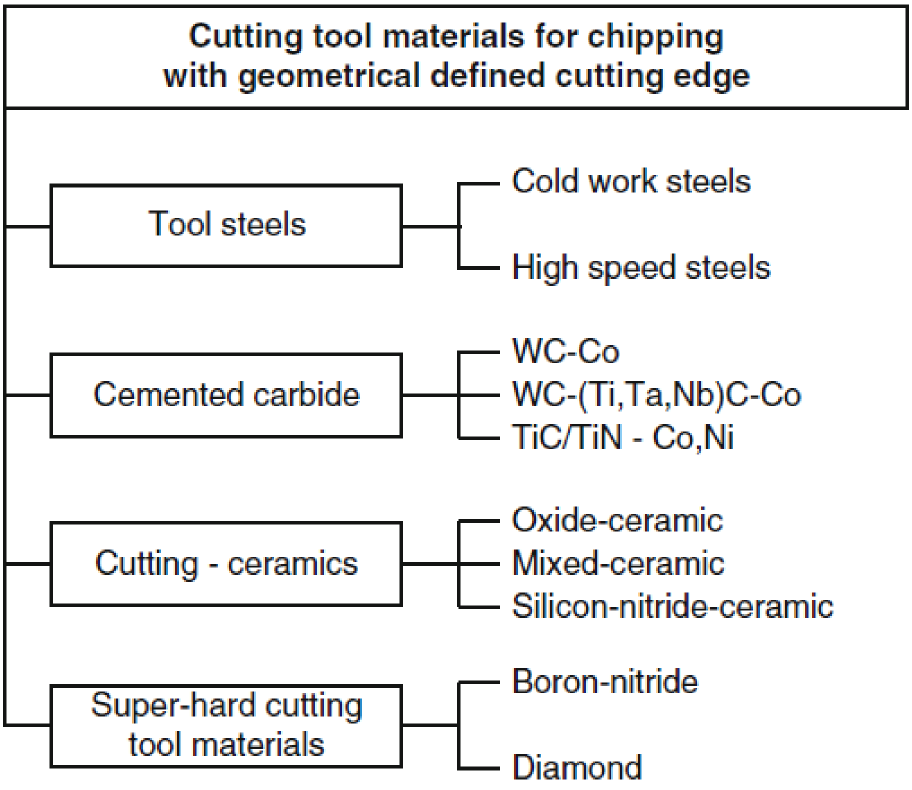


Figure 1.6.1.1 Materials for cutting tools [27].

Comparison of cutting material hardness and toughness can be seen in the figure below.

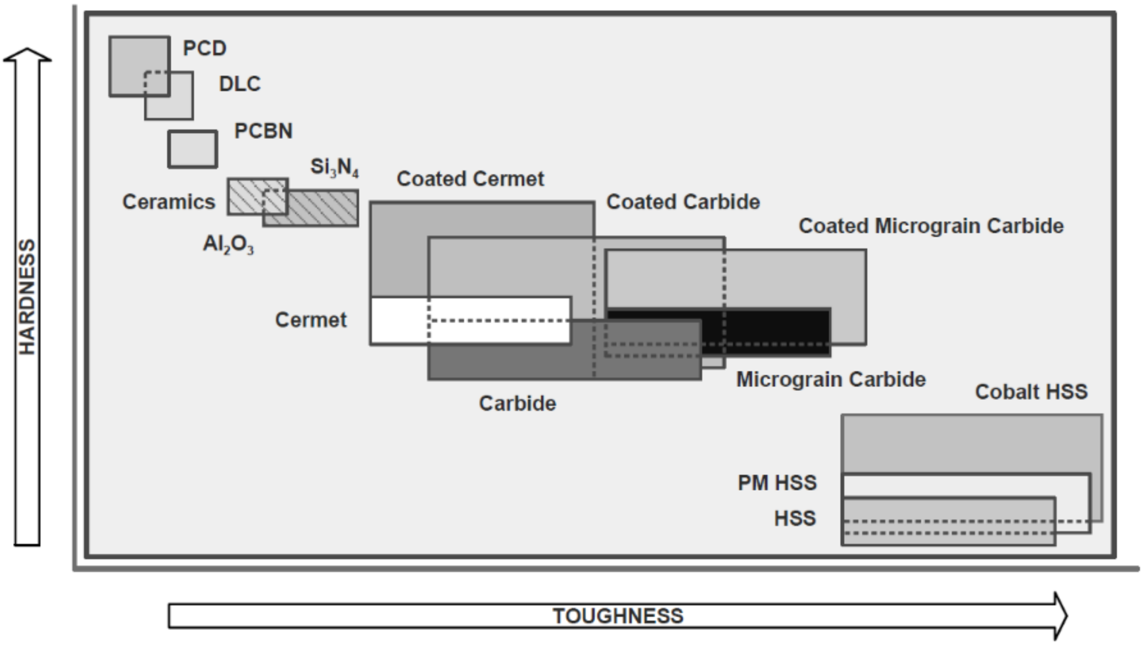


Figure 1.6.1.2 Comparison of hardness and toughness of tool materials [48].

Hardness of the tool should always be from 3 to 5 times more important than hardness of the machined material at ambient temperature [34].

As can be seen from the figure above, tools are either hard or tough. Hard materials are fragile. Ideal cutting tool material would be located on the top right corner of the figure, both high in hardness and in toughness.

1.6.2 Cutting tool geometry for turning

Following surfaces and curves can be defined on a general turning tool.

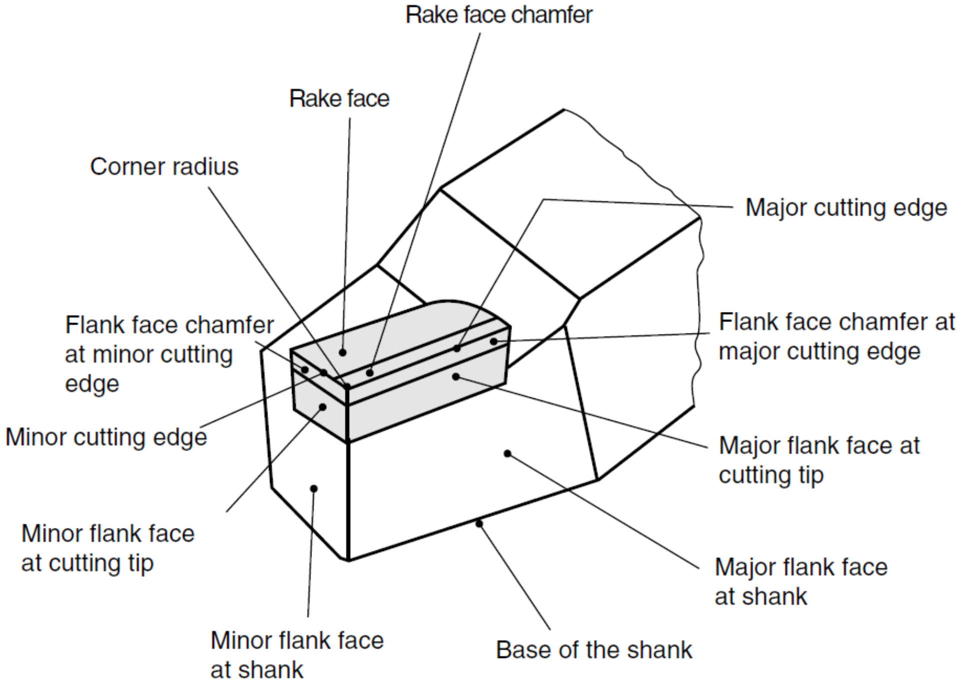


Figure 1.6.2.1 Geometrical element of a turning tool according to DIN 6581 [17].

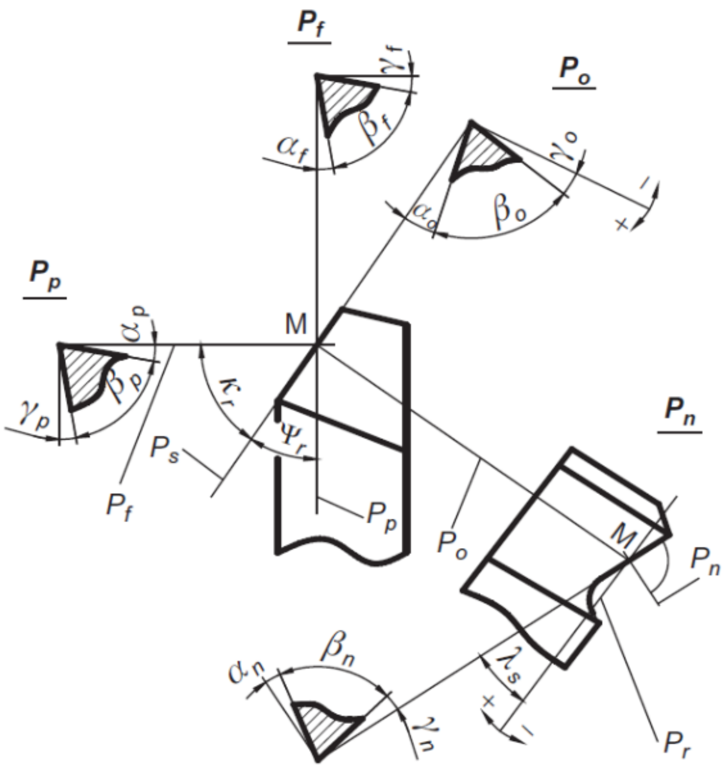


Figure 1.6.2.2 Simplified tool geometry [23].

Tool angles and working angles are measured as [23]:

Angle name and symbol	Measured between face:	And plane:	Measured in plane
Tool normal rake γ_n	A_γ	P_r	P_n
Working normal rake γ_{ne}	A_γ	P_{re}	P_n
Tool normal clearance α_n	A_α	P_s	P_n
Working normal clearance α_{ne}	A_α	P_{se}	P_n
Tool cutting edge κ_r	P_s	P_f	P_r
Working cutting edge angle κ_{re}	P_{se}	P_{fe}	P_{re}
Tool cutting edge inclination λ_s	S	P_r	P_s
Working cutting edge inclination λ_{se}	S	P_{re}	P_{se}
Tool-included angle ε_r	P_s	P'_s	P_n
Normal wedge angle β_n	A_γ	A_γ	P_n

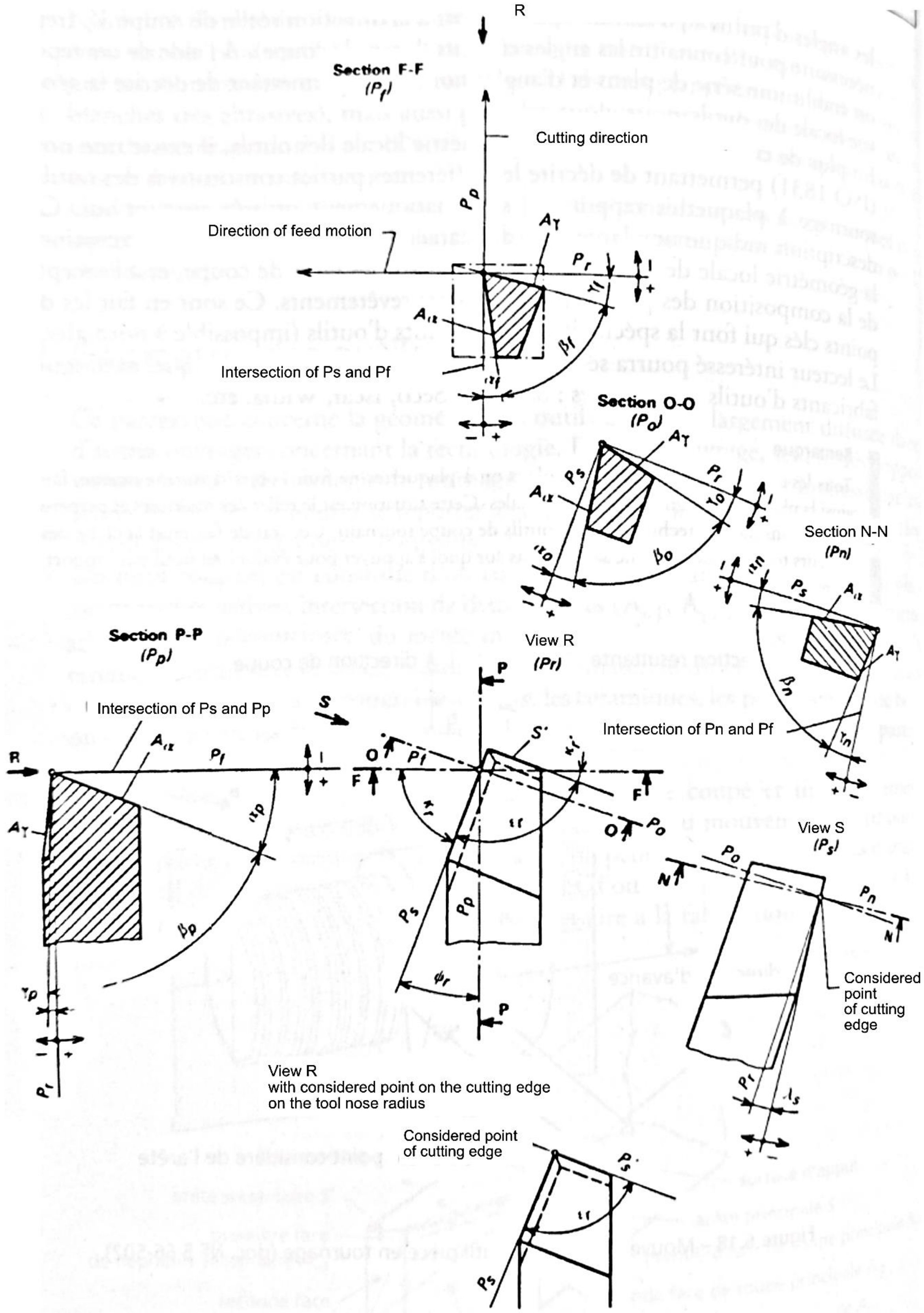


Figure 1.6.2.3 Definition of cutting angles by norm NF E 66-502 [34].

1.6.3 Tool wear

Tools get used over time. They are multiple types of tool wear. By looking at these, we can determine if a tool is not useable anymore.

There are three phenomes causing tool wear with sub-specifications [22]:

- thermal damage:
  - due to thermal diffusion,
  - due to plastic deformation,
  - due to chemical reaction,
- mechanical damage:
  - chipping,
  - abrasion,
  - fracture,
  - fatigue,
- adhesion:
  - welding of chip material onto the cutting edge of the tool.

Parameters influencing tool life are:

- geometry of the cutting tool,
- cutting conditions,
- cooling fluid used,
- material of tool,
- material of workpiece.

By changing cutting conditions, tool life can be optimised (for correct geometry and materials consider already determined).

The three most important cutting conditions that influence tool life are:

- depth of cut a_p
- feed f
- cutting speed v_c

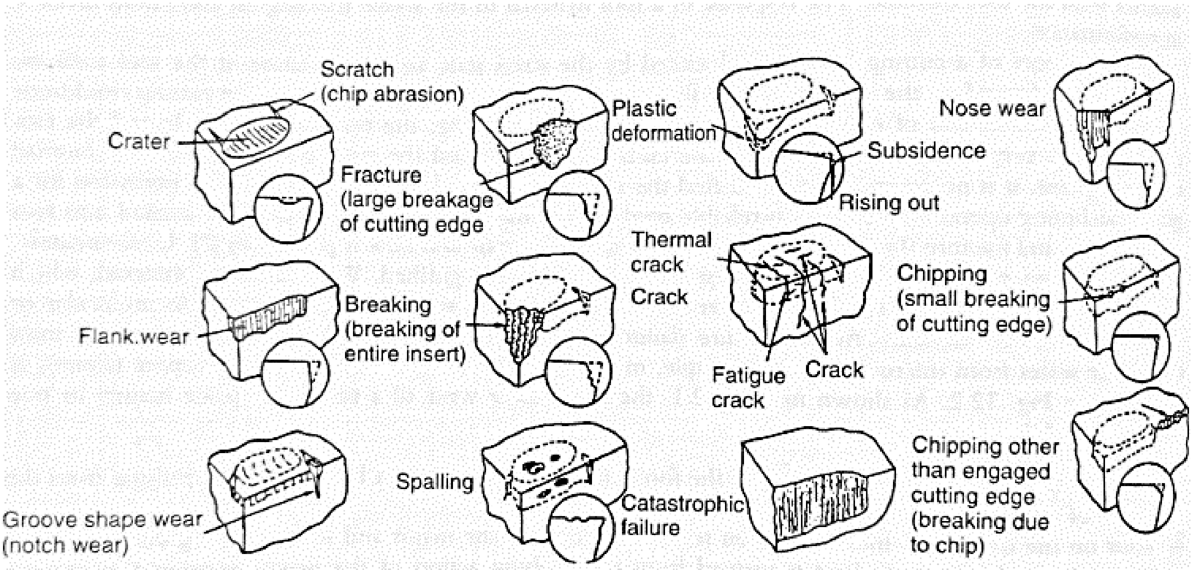


Figure 1.6.3.1 Types of tool wear [22].

1.6.3.1 **Taylors equation for tool life**

Taylor's equation is an equation describing relation of tool life depending on cutting speed and other cutting parameters. Taylor's equation has two forms:

- simplified Taylor's equation,
- developed Taylor's equation.

Tool life depending on cutting speed can be approximated as an exponential function as shown in the figure below.

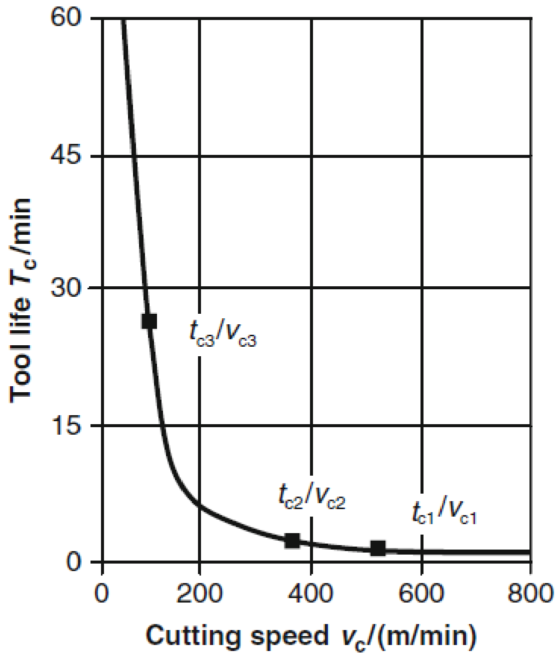


Figure 1.6.3.2 Example of tool life depending on cutting speed [27].

Exponential function shown in logarithmic system has an allure of a straight line. Straight line can be mathematically described as:

$$y = a \cdot x + b \quad (5)$$

Where a and b are constants.

Therefore the equation for tool life in logarithmic form can be expressed as:

$$\log(T_c) = a \cdot \log(v_c) + b \quad (6)$$

When the logarithm in the equation above is antiloged, simplified Taylor's equation for tool life is obtained. Simplified Taylor's equation of tool life is described by the following equation:

$$v_c \cdot T^n = C \quad (7)$$

Modified (developed) Taylor's equation for tool life is:

$$VT^n f^a d^b = C \quad (8)$$

Where T is tool life, V is v_c, f is feed, and others are constants.

Tool life has a general tendency:

- a_p increasing lowers tool life,
- f increasing lowers tool life,
- v_c increasing lowers tool life by causing tool wear quicker.

Tool life can be prolongated by appropriate coatings. A coating with higher hardness is deposited on the surface of the tool to improve tool wear. Less hard tool underneath has better toughness. This combination of materials assures longer tool life without sudden tool fractures compared to overall harder tool material. It also keeps cost lower.

There are two main methods of coating deposition:

- Physical vapour deposition (PVD),
- Chemical vapour deposition (CVD).

1.7 THREADS

Threaded joints are a method of joining parts.

Helical threads are a mechanical method of creating a helical link between threaded parts which changes angular motion to linear motion [4].

A helix is a curve created by tracing position of point A on a cylindrical surface with two simultaneous movements:

- rotation XY of point A around axis of the cylinder,
- translation parallel to the axis of the cylinder [5].

Threaded joints (for example screw and nut, bolts) are an important type of joints because a threaded fastener is demountable [4].

1.7.1 Threaded joints

Threaded joints are a way of assembling two parts together by thread fastening. The most commonly known example of a threaded joint assembly is by a screw and a nut.

In this study case the function of threaded joint plays and important role for multiple functional elements of the studied part.

Advantaged of assembly by threaded joints are:

- The assembly is demountable.
- Threads are widely standardised,
- Threaded joints are resistant to forces in multiple directions (depends on type of thread).

Threaded joints are present on the studied part, both external and internal.

Thread terminology is shown in the following figure.

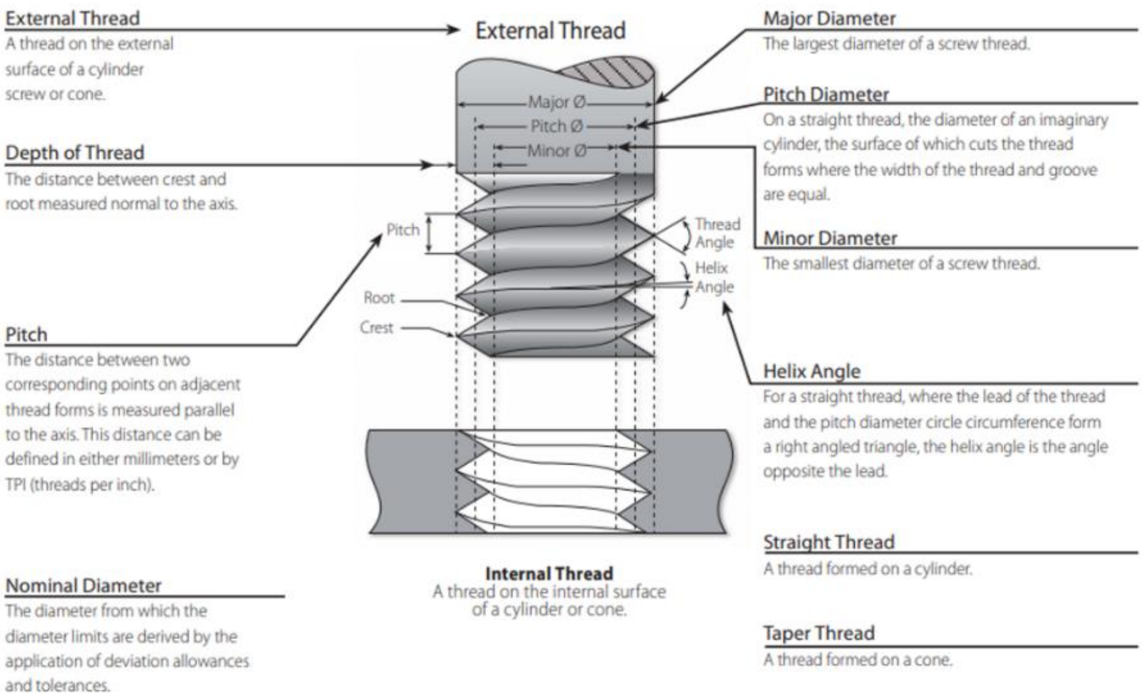


Figure 1.7.1.1 Terminology for external and internal threads [15].

1.7.2 Types of thread

There are many internationally normalized profiles of threads, for example [6]:

- ISO thread (also called metric threads),
- trapezoidal thread,
- UN (Unified National) thread,
- Whitworth threads,
- pipe threads,
- knuckle threads.

On the studied part, only metric threads are used.

1.7.3 Metric thread standards

The profile of a metric (ISO) thread is described in the following figure:

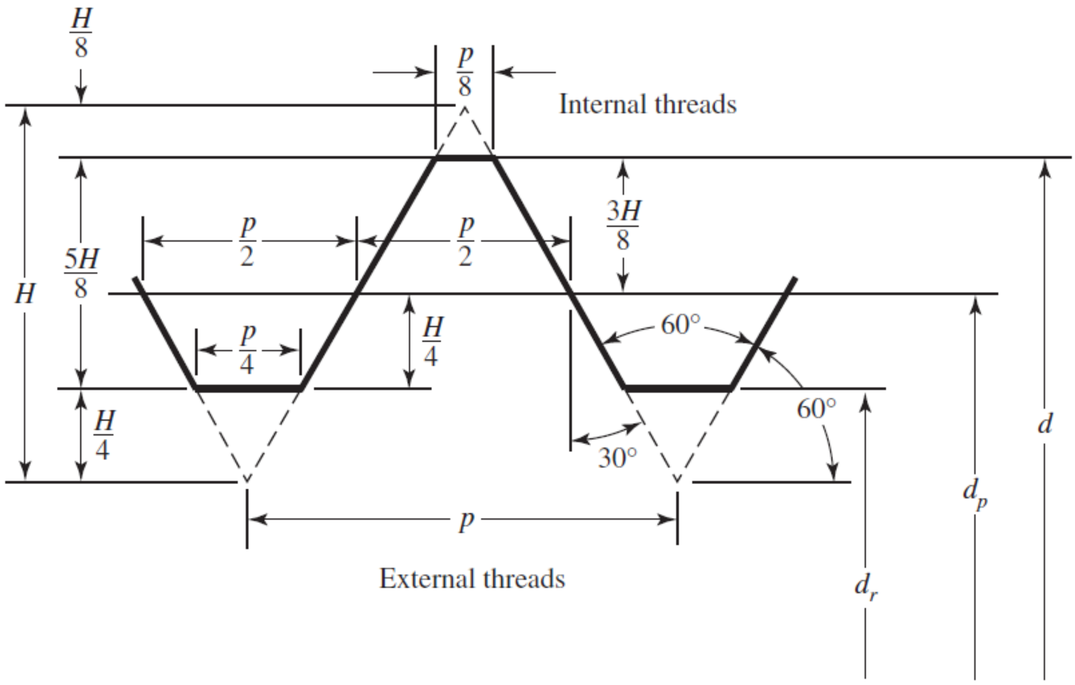


Figure 1.7.3.1 Metric thread profile specification [4].

Where symbols have following meaning [4]:

- p… pitch [mm],
- H… $\frac{\sqrt{3}}{2}p$ [mm],
- d… major diameter [mm],
- d_p … pitch diameter [mm],
- d_r … minor diameter [mm].

1.7.4 Bolts

Bolts or screws are mechanical parts that have an exterior thread. The studied component is defined as a volt of large diameters

Maximum charge that a bolt can withstand can be calculated as [6]:

$$F_{maxi} = 0.9 \cdot R_e \cdot Sq_{eq} \tag{9}$$

Where symbols have following meaning:

- F_{maxi} … maximum charge in traction [N],
- R_e … elastic limit of bolt material [MPa],
- S_{eq} … air of thread resisting to charge [mm^2].

Tightening torque to tighten a bolt be calculated as [6]:

$$C = (0.16p + 0{,}583 \cdot f_f \cdot d_2 + 0.5 \cdot f_t \cdot D_m) \cdot F \qquad (10)$$

Where:

- C… tightening torque [Nm],
- p … pitch [mm].

1.7.5 Thread fabrication methods

There several methods of creating a thread, for example:

- cutting,
- forming (form tapping, rolling),
- 3D printing,
- casting.

Form tapping and form cutting are going to be compared in the following section.

1.7.5.1 Form tapping

Creating a thread by deformation is called form tapping. During tapping no chips are created, instead the material is little by little deformed into the form of the thread. The advantage is that material is hardened by this deformation which makes the thread more resistant to wear. For internal form tapping, there is a risk of tool breakage. If the tapping tool breaks in the hole, the piece is usually ruined and is to be disposed of. For this reason, tapping is not usually used for workpiece that have a great added value (for example big aeronautic pieces). Other methods are preferred for such applications.

1.7.5.2 Thread cutting methods

On the other hand, cutting a thread means that chips are created. For the studied component, only threading by cutting was used.

There are multiple thread cutting methods, for example:

- thread turning,
- thread milling,
- tapping.

Thread tapping has the same problem as form tapping – if the tool breaks inside the hole, the piece is to be disposed of.

There are three basic types of taps [49]:

- straight flute taps,
- spiral flute taps,
- spiral point.

1.7.6 Thread turning

Both internal and external threads can be fabricated by turning if the thread is concentric with the axis of the part in which is the workpieces rotation during a turning operation.

Both right hand threads and left-hand threads can be achieved by turning as is illustrated in the figure below.

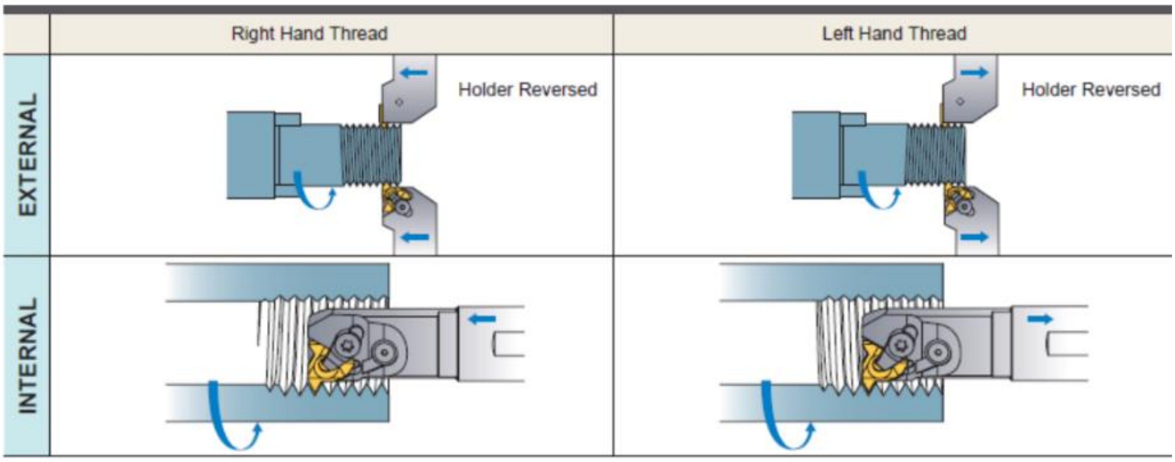


Figure 1.7.6.1 Thread turning methods [50].

Depending on the position of the threading insert at every pass, different infeeds are possible.

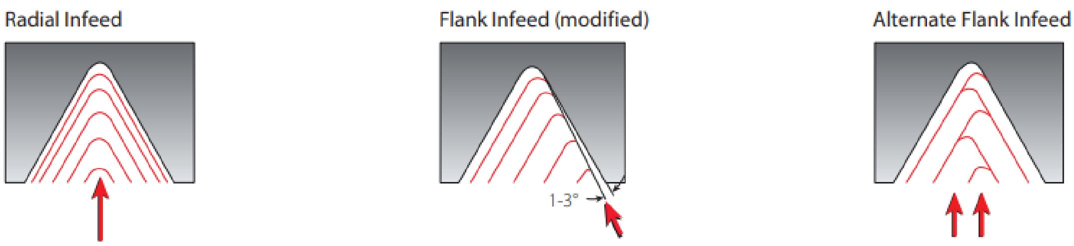


Figure 1.7.6.2 Thread infeed methods [15].

Different infeeds produce different types of chips for different materials.

1.7.7 Thread tapping

Internal threads are often machined by thread tapping on lathes while keeping the feed strictly equal to the pitch threads. Taps need to have the same diameter as the threaded hole [7].

There is a risk of tool breakage in the hole. Because tapping tools have the same diameter as the threaded hole, taking out broken tapping tool is difficult and often results in scrap workpieces.

Long unfragmented chips are also typical for tapping operations. A good alternative for thread tapping is thread milling.

1.7.8 Thread milling

Thread milling is a method of thread machining. Both external and internal threads can me milled.

Thread milling is well applicable even for hard to machine materials [8].

Thread milling of internal threads is detailed below.

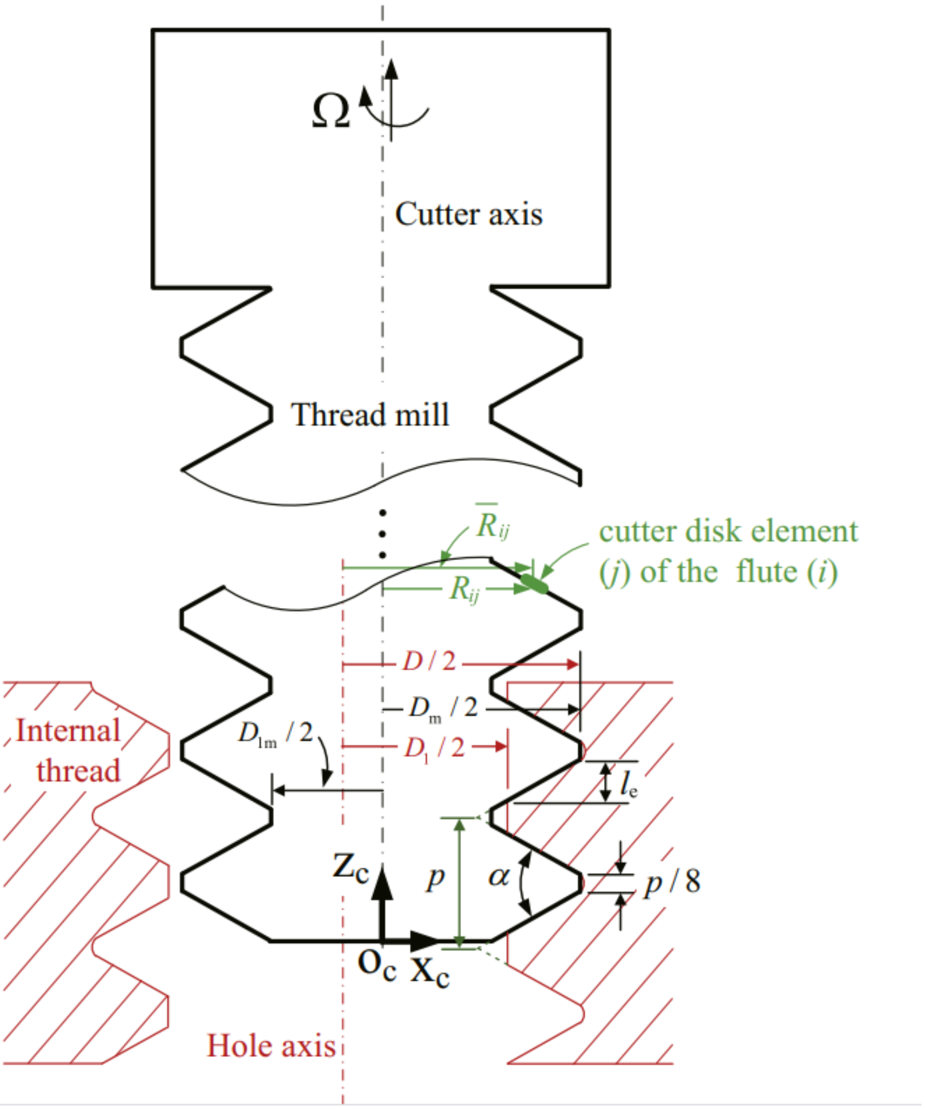


Figure 1.7.8.1 Internal thread milling [7].

Where symbols have following meanings [7]:

- D … nominal diameter of the internal thread [mm],
- D_1 … minor diameter of the internal thread [mm],
- D_m …maximum diameter of the thread mill [mm],
- D_{1m} minor diameter of the thread mill [mm],
- α … thread angle [°],
- p … thread pitch [mm],
- l_e axial length related to slope part of the thread [mm],
- X_c, Y_c, Z_c rotating coordinate system on the cutter, positive direction of Y_c is from the cutter's centre to the hole's centre.

Example of trajectory of a point on a thread milling cutter is presented in the figure below.

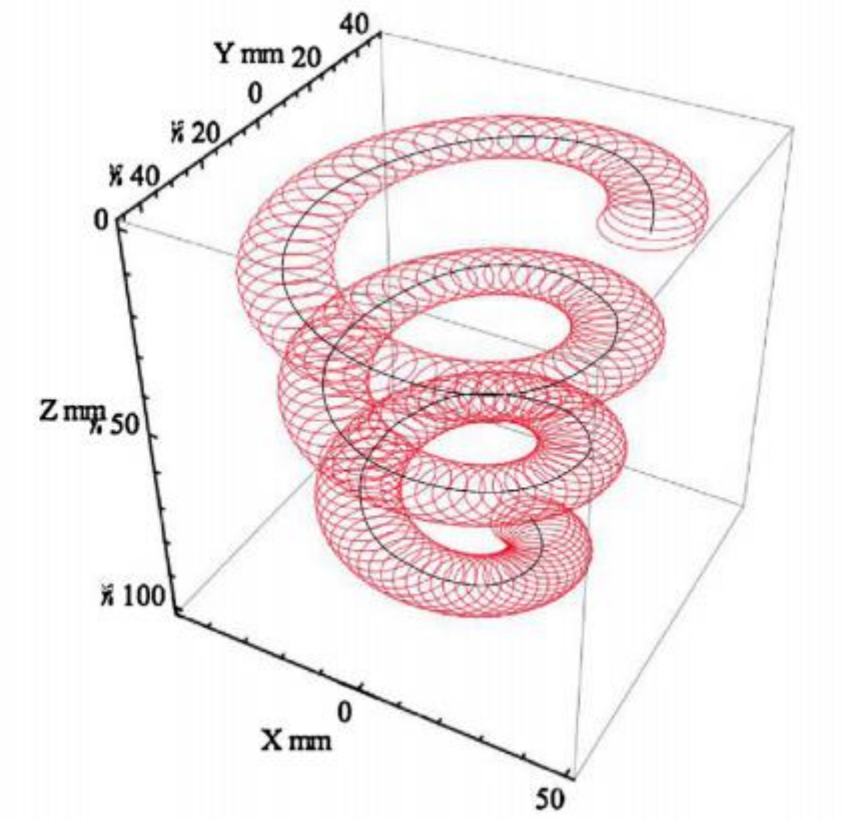


Figure 1.7.8.2 Thread milling cutter trajectory of a point on the cutting edge for API thread [51].

Thread milling cutter follows a helical path.

Nature of tool trajectory that is recommended for optimal results by tool producer Walter Tools is displayed in the following figure.

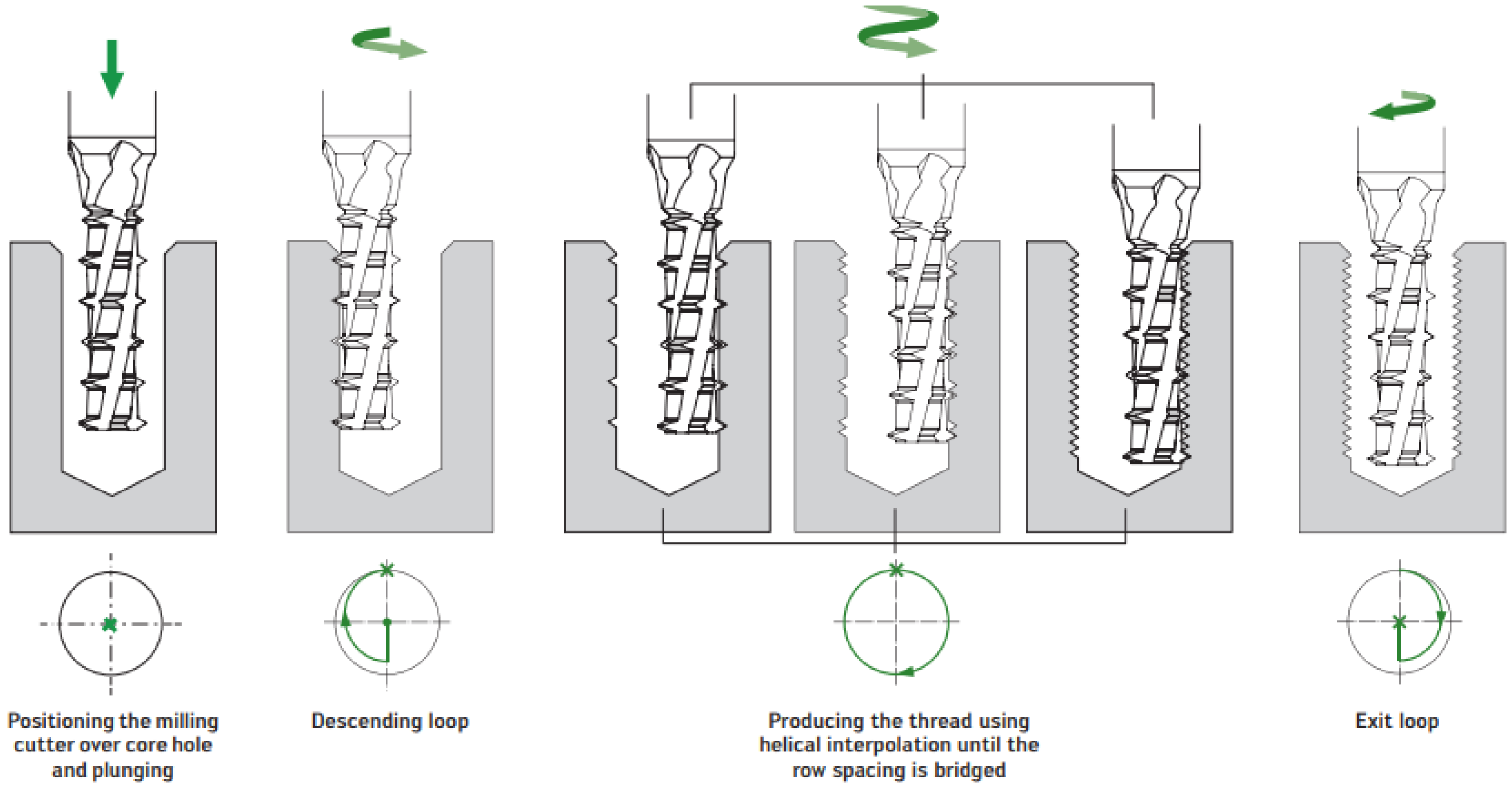


Figure 1.7.8.3 Thread milling with optimal trajectory principle [52].

The entry by half revolution in descending loop decreases the level of interferences [7].

1.7.9 Interferences during thread milling

Because of interferences during the thread milling, generated thread profile (GTP) and nominal thread profile (NTP) are not equal. Between GTP and NTP there is a radial error, either overcut of undercut [53].

An algorithm for interference calculation described in literature was used to attempt to calculate interferences and tool radius corrections.

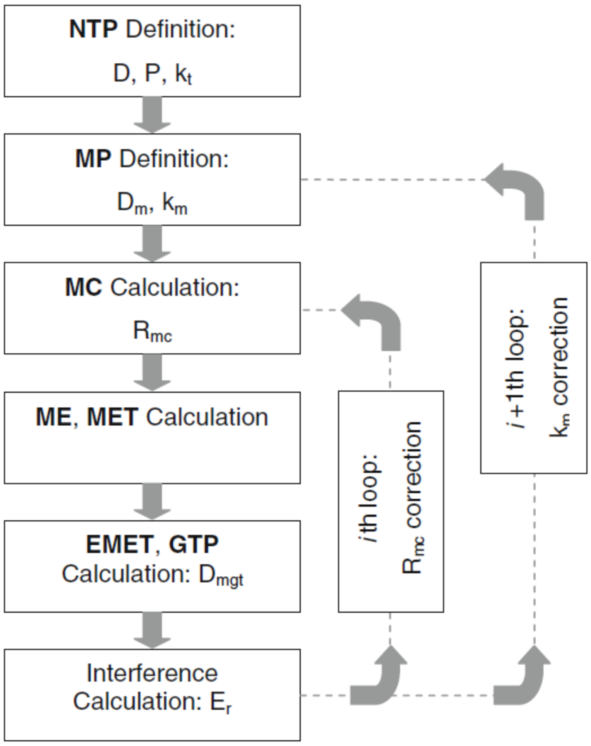


Figure 1.7.9.1 Algorithm of computation of interferences during thread milling according to [53].

Where symbols have following meaning:

- NTP …nominal thread profile
- NTS … nominal thread surface,
- D … nominal diameter of the internal thread,
- P … pitch
- k_t …reduction coefficient of the thread profile height,
- MP … mill profile (profile of milling cutter),
- MC … mill centre trajectory (helix)
- R_{mc} …helix radius of the mill centre trajectory,
- ME …mill envelope (envelope generated by the milling cutter),
- MET …mill envelope trace (projection of circle in ME)
- EMET …envelope of the mill envelope trace in plane (O, E1, E3),
- GTP … generated thread profile,
- E_r …error.

One iteration of the proposed algorithm was inserted into a spread sheet that calculated the error during thread milling and radius correction. Detailed version of the calculations can be found in attachment.

Precise value of minimal error could not be calculated because tool producer does not give all tool parameters needed for the precise computation.

Example of calculated values using fictive value of parameter called reduction coefficient of the mill profile height k_m of the milling cutter for threading of M16x2 with Walter Tools TC620-M16-A1E-WB10TJ cutting tool is presented on the figures below.

Value of k_m was estimated as $k_m = 0.111$.

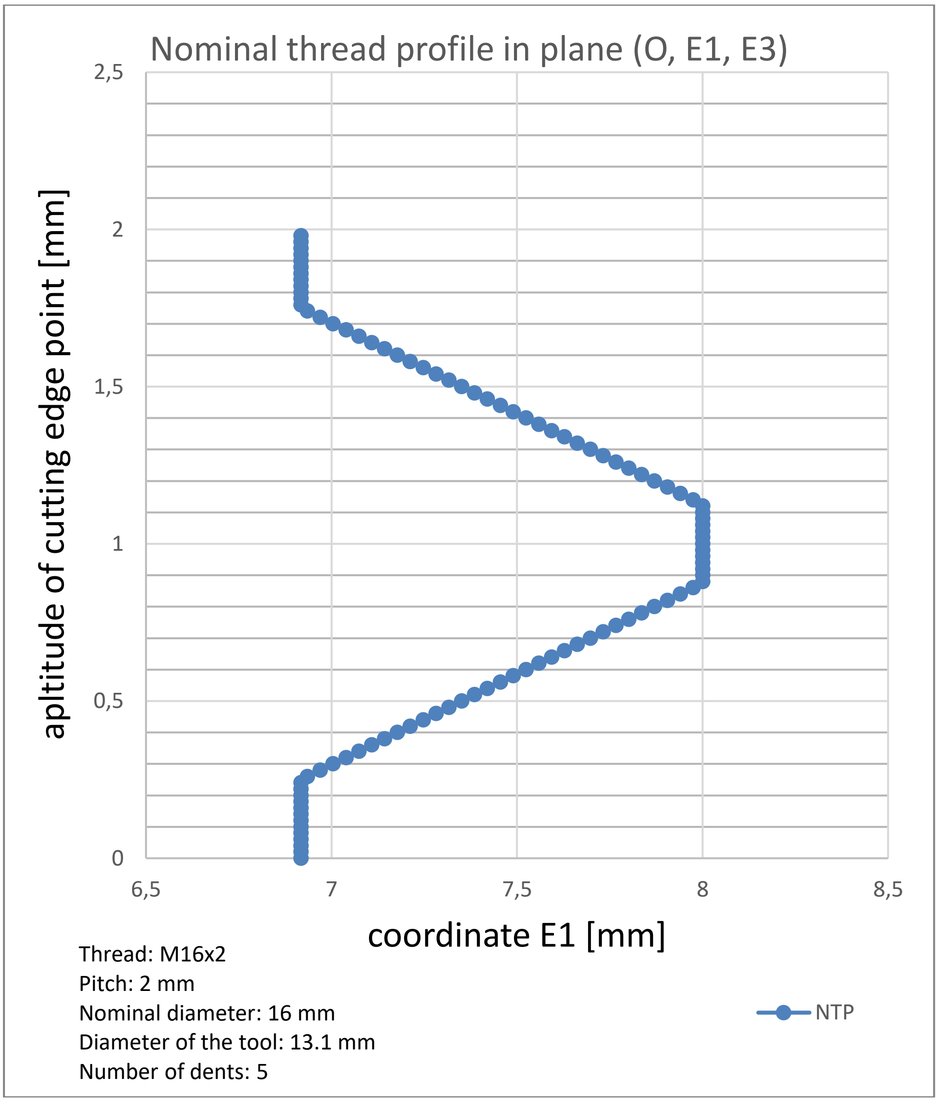


Figure 1.7.9.2 Nominated thread profile of M16x2 metric thread calculated with algorithm from the literature [53].

Hypothetical interferences if $k_m = 0.111$.

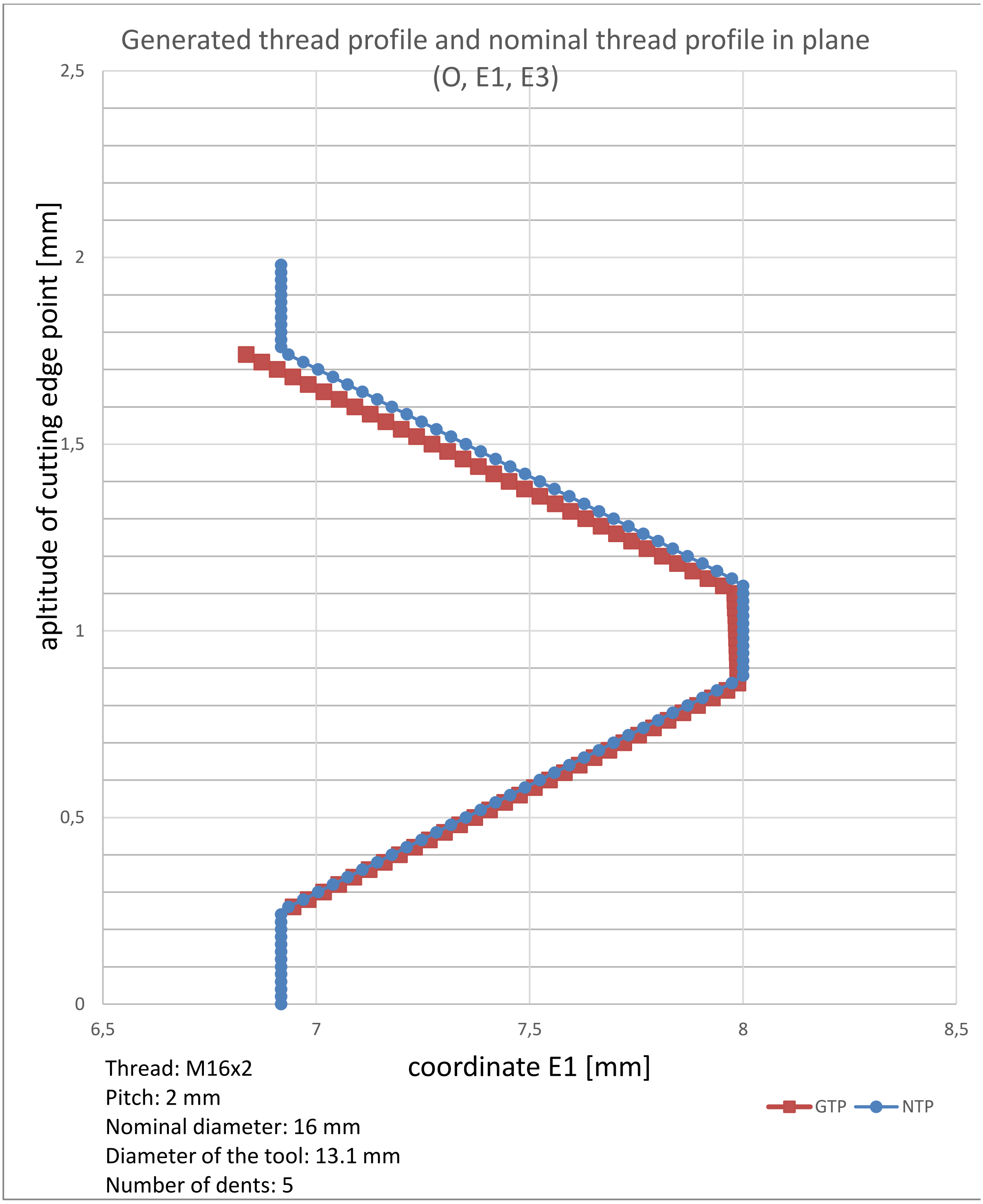


Figure 1.7.9.3 Generated thread profile and nominal thread profile interposed calculated with algorithm from the literature [53].

The value of error (in horizontal direction) is displayed on the figure below.

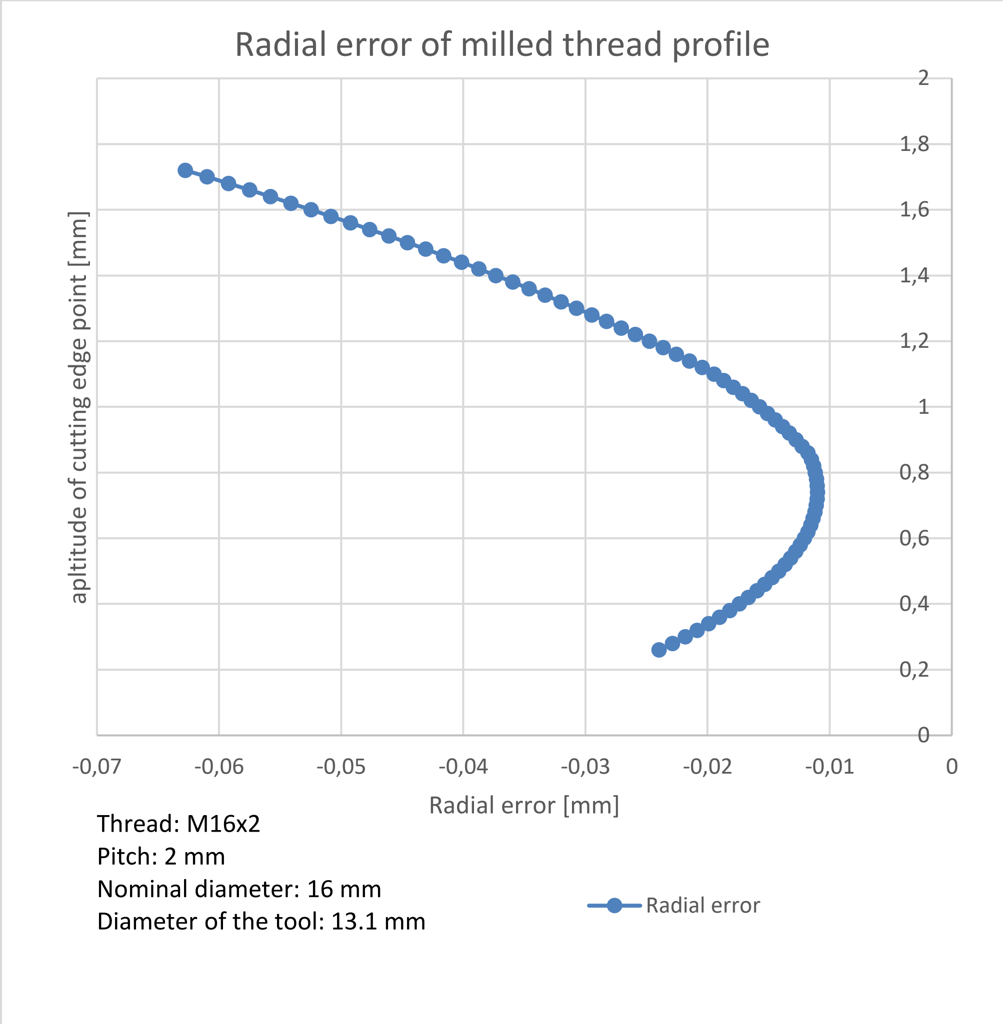


Figure 1.7.9.4 Value of error between nominal thread profile and generated thread profile calculated with algorithm from the literature [53].

Details of the computation can be found in the annexe, all algorithm and equations used can be found in literature [53].

1.8 AUTOMATION

Automation is an effective way of achieving cost-efficient production and has an important role in industrial context. It allows avoiding heavy, repetitive, dangerous or time-consuming manual work. At this point of automation development, there are still tasks that cannot be automated, because machines have not yet the level needed [54].

1.8.1 Definition of automation

There are multiple definitions of automation. For example, a definition of automation according to the Oxford Learner’s Dictionaries is *the use of machines to do work previously done by people* [55].

This project is concerned by industrial automation by which refers to automation of manufacturing, material handling and quality control.

1.8.2 Degrees of automation

A level of automation of a system can be distinguished. There exist multiple definitions of levels of automation.

Levels of automation according to their production flow (in increasing order) are defines as:

Conventional machines: no or minimal automatization, manual control by operator needed.

Numerical control machines: machining process controlled by NC program, presence of operator needed to supervise the process

Automats or semi-automats: minimal supervision needed, feed of workpieces generally not fully automatized, placing of workpieces and manual removal of machined parts performed by operator.

Single purpose machines: all automatized, even flow of workpieces is automated.

CNC machines have already a degree of automation. By adding a robot, other tasks can be automatised.

On the following chart, characteristics based on level of robotization can be seen.

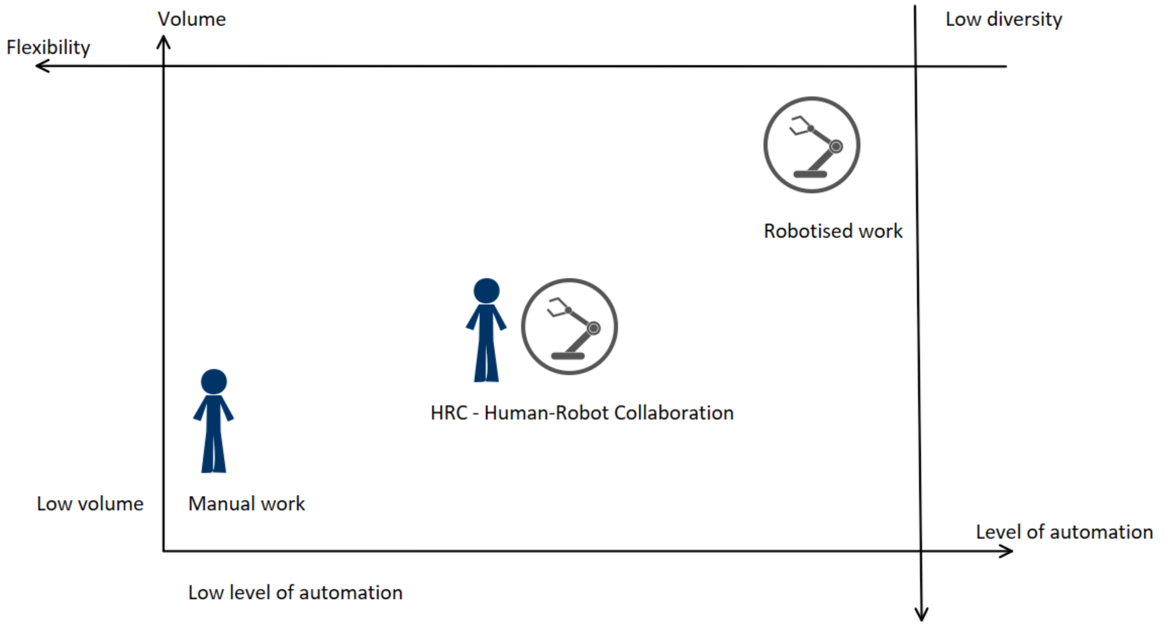


Figure 1.8.2.1 Basic distinction of manual and robotised work.

Robotised tasks have low level of flexibility. For example, if a problem occurs, the system might not be able to solve it and needs an operator for solving it. On the other hand, using a robot raises the volume of work.

When implementing a robot in order to raise the level of automation, different types of human-robot interaction (HRI) can be distinguished.

Human-robot interactions can be classified based on different criteria such as the sharing of workspace,

Bender et al. described five levels of interaction [56]:

- cell,
- coexistence,
- synchronisation,
- cooperation,
- collaboration.

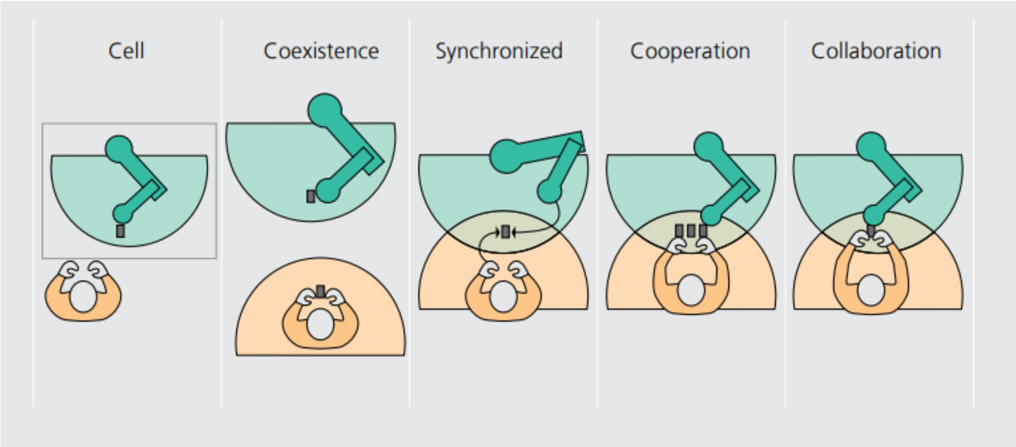


Figure 1.8.2.2 Human-robot interaction classification based on level of shared workspace [56].

Collaborative robots are especially interesting because they can work in presence of human without danger of hurting them. This way the collaborative robot

Industrial robot

Implementation of industrial robots consist of using and programming an industrial robot to perform tasks in place of a human operator.

Industrial robots have potential to boost the productivity and precision and replace repetitive manual work.

There are many types of industrial robots, for example:

- Articulated,
- Cartesian,
- SCARA
- Parallel,
- AGV = Automated Guided Vehicle.

For feeding a CNC machine, articulated robots are often used because they are compact, easily movable with large range of motion.

Safety measured must be taken when implemented automated systems. For example, for industrial robots are often in safety cages with laser detectors to detect presence of material and/or humans.

1.8.3 Automation in machining

Automation in a machining process consists of two parts:

- Eliminating unprogrammed interventions of the operator,
- Automating programmed interventions of the operator.

Example of unprogrammed intervention of operator is changing of a tool when it breaks or taking tangled chips out of the chip conveyor.

Example of a programmed intervention is tool change after a determined time or taking measurements to ensure respect of dimensional and geometrical tolerances.

For context of industrial automation and this case study, automatization of the task of feeding workpieces into the CNC machine and taking out machined parts was considered. Before automating this workpiece feed process, the machining itself need to be optimised in order to function without unprogrammed interventions of its operator.

1.9 OPTIMISATION

Optimisation of the machining process aims to results to gain in one or more of following aspects:

- Chip breaking and chip evacuation (safety),
- Economy
- Productivity.

To gain in productivity, it is best to work with at maximal feed and depth of cut that are compatible with [19]:

- The machine,
- Chip breaking,
- Geometry and resistance of the tool,
- Rigidity of setup.

Higher feed results in shorter tool life. Increasing feed can be accompanied with lowering of the cutting speed in order to compensate the tool life lost by increased feed. This can result in rise in productivity while keeping the same tool life [19].

For economical aspect, optimisation consists of lowering all costs.

There are four costs of production by machining [22]:

- Machining cost,
- Tool cost,
- Tool change and setup cost,
- Product handling cost.

For economical aspect, there are three principal factors:

- Production cost per unit,
- Production time per component,

- Profit rate.

There are multiple optimisation criteria when optimizing the cutting parameters [19]:

- Minimal machining cost,
- Minimal machining time,
- Volume of chips per cutting edge.

1.9.1 Machining costs

Example of repartition of machining cost is displayed in the following figure.

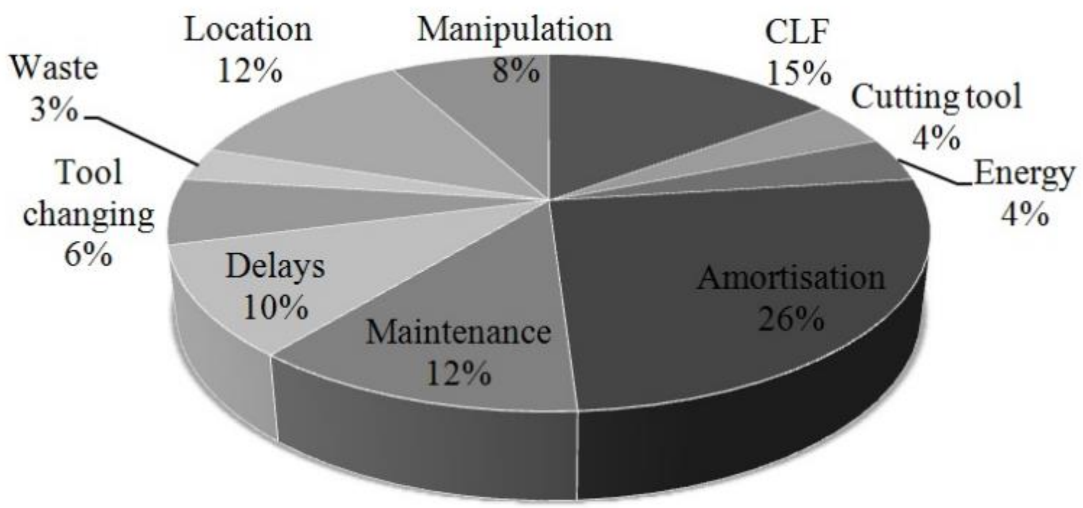


Figure 1.9.1.1 Machining costs by percentage of total cost [57].

Amortisation and maintenance of the machine represent a big part of machining cost. Especially for machines that are not very rigid, it is important to choose machining strategies that present low risk for the machine. Cutting and lubrification fluids represent up to 15% od the machining costs, methods of minimal volume of those fluids can significantly lower this important part of the machining costs.

1.9.2 Optimisation gains

An industrial context causes that economics (profit rate, machining cost) of the fabrication process need to be considered. Even though main objective can be different, gaining profit by optimizing the process is always welcomed.

The best timing for optimisation is during the preliminary phase before the actual fabrication process is installed and used. As can be seen in the figure below, if optimisation intervention comes later, during fabrication, the potential gains get significantly lower [34].

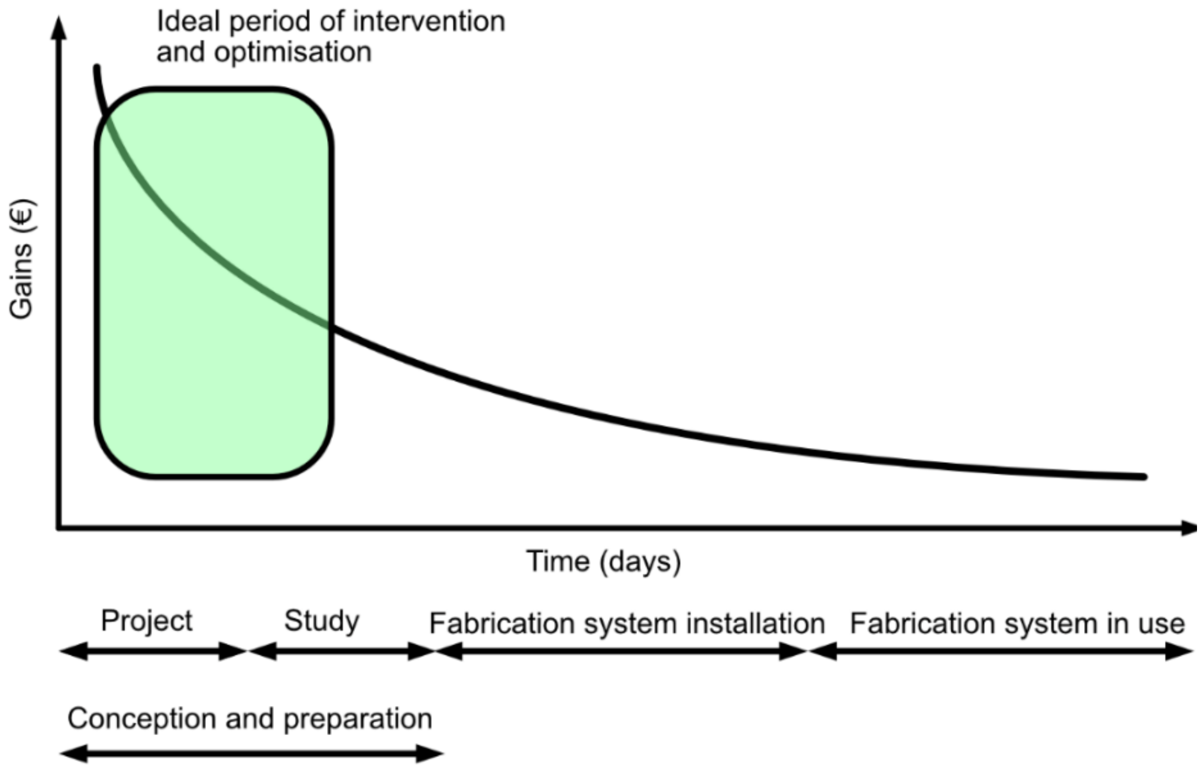


Figure 1.9.2.1 Gains depending on phases of fabrication system development re-drawn accordingly to [34].

2 CASE STUDY

This case study was conducted during an internship. Goal of the internship was to optimize fabrication by machining of a family of parts – head bolts, with aim to minimize the machine operator’s interventions during the cutting process. Especially unprogrammed intervention and door opening were to be eliminated. The company wish was to enable increasing the level of automation in a future project. Without optimisation of machining process and cutting conditions next level of automation would not be possible.

The case study consisted of study, observations and analysis of the current fabrication process of a group of components for cone crushers. The component fabrication process was realised by machining. Machining and material handling were analysed during the case study. The case study was followed by optimisations, therefore it was critical to first identify the problems encountered during the process.

2.1 INDUSTRIAL CONTEXT

The case study is concerned by an industrial product. Before analysing the fabrication process, the industrial context is going to be elaborated in this chapter.

Firstly, the company Metso is going to be briefly introduced. Secondly, cone crusher are going to be described, because the studied parts are components of a Metso cone crusher.

2.1.1 Company introduction

Metso is a finish company with history in Finland, Sweden and France and it was created by connection of two corporation – Valmet Corporation and Rauma Corporation in 1999. These corporations regrouped important leaders in diverse branches of the industry. For example a Swedish company the Sund Bruk ironworks (established1868) and a Finish company the Nordberg Manufacturing Company (established in 1886) to name a few. [58]

The name Nordberg is still-well known in the industry for reliable machinery as machines with this name were being fabricated even after multiple fusions of companies.

In France, the part of the group Metso started as company Bergeaud and Bruno in 1895 in Mâcon. Then it became Ateliers Berheaud Mâcon (ABM) in 1919 and began its history of providing solutions for industry of aggregates and crushing minerals. The company Bergeaud and Bruno became a part of Rauma-Repola in 1987. Rauma was united with Valmet in 1999 to create a new company and therefore Metso was founded. In 2013 the company Metso split into two entities: Metso Corporation and Valmet Corporation. In 2019 a cooperation of two companies Metso Minerals and Outotec was announced to the fusion occurred in second part of year 2020 creating a new company: Metso Outotec [58].

The fusion of Metso and Outotec occurred during last weeks of the internship. As for most part the employing company was called Metso, the name Metso is going to be used when referring to the company. It should be noted that the company than became Metso Outotec at the end of the internship and the term “Metso” refers to both Metso and Metso Outotec.

Metso is active in multiple industrial branches:

- mining,
- aggregates,
- valves,
- metal recycling,
- waste recycling [59].

The case study conducted was for a part in the Aggreagated branch of Metso. The centre at Mâcon, France, there is a long history of fabricating heavy machinery and till today the branch of Metso in Mâcon develops and produces solutions for the aggregate industry. In the aggregate branch of Metso, machines that are used for mineral and rock crushing to produce gravel and sand. Also machines for screening the and transporting the aggregates are developped in the Aggregates branch of Metso [60].

There materials crushed can be referred to as mineral, rocks or aggregates. The word “aggregates” is a generic term that is used for crushed rocks and gravels used for construction purposes or water filtration [61].

The Metso Aggregate branch solution can also be used for construction and demolition material crushing before they are recycled [60].

Gravel and sand are key building materials for building and road construction and other industries. For example, the average daily consumption of aggregates is 18 kilograms per person per day (or 50 tons per person per year). They are used for construction, cosmetics (tooth paste for example), electronics and many other sectors [61].

2.1.2 Types of crushers

Crushers serve to crush material, usually aggregates but also material before recycling. Crushing has for aim to reduce the size of the crushed material particles. During the process of reduction of the size of material, one or multiple crushing circuits are needed [62].

By choosing a good crushing solution, desired aggregate size and also shape can be obtained [63].

There are two main types of crushers that differ by their mode of functioning [62]:

- compression crushers
- impaction crushers.

The difference between compressive crushers and impaction crushers is in the mode of transfer of force from the crusher to the material. For impaction crushers the transfer is much more quicker and tent to produce less dust than when using a compression crusher [62].

The company Metso fabricates three main types of compressive crushers [64]:

- gyratory crushers,
- cone crushers,
- jaw crushers,

For all three types of compression crushers, there is a mobile and fixed part, both protected by wear parts. In case of a jaw crusher, there is a reciprocating jaw and a fixed jaw. In case of gyratory and cone crushers the mobile part is a cone head protected by a mantle and the fixed part is a concave protected by a bowl liner [62].

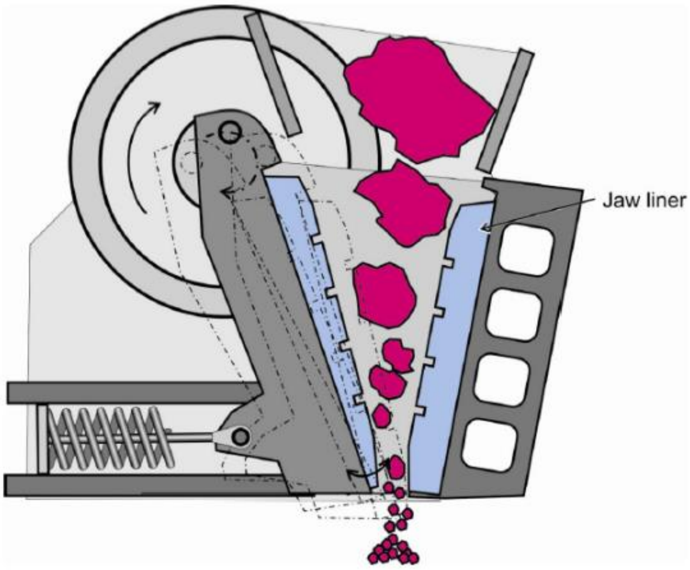


Figure 2.1.2.1 Jaw crusher illustration [62].

Cone crushers and gyratory crushers look similar as can be seen in the following figure.

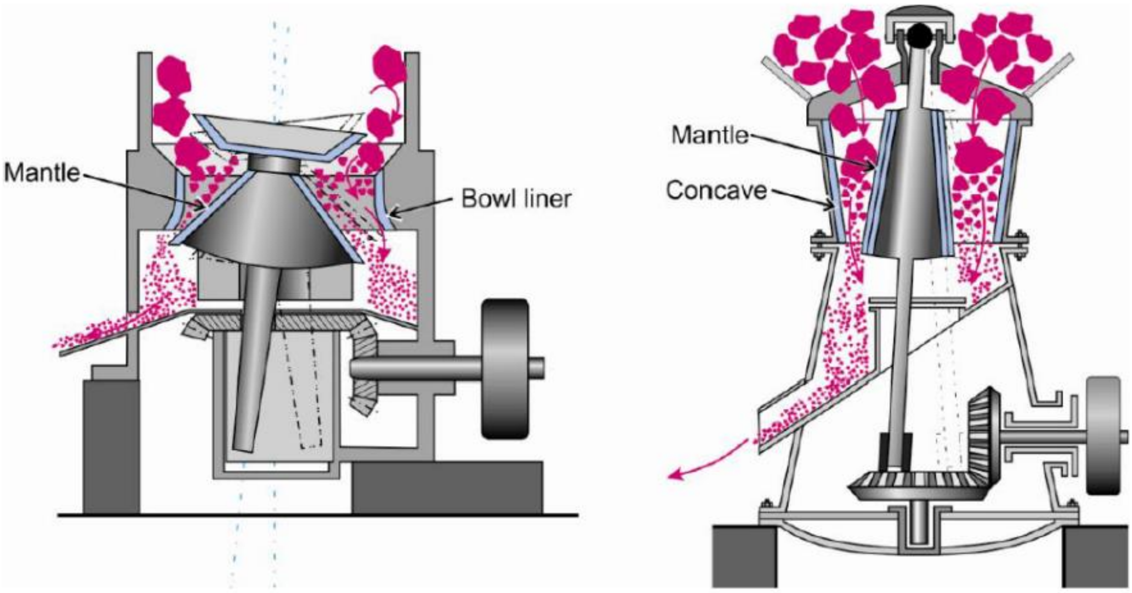


Figure 2.1.2.2 Compressive crushers – cone crusher (on the left) and gyratory crusher (on the right) [62].

The difference between a gyratory crusher and a cone crusher is in the pivot point of the mantle.

The pivot point of a crusher is defined as point of intersection between the axis of the moving mantle and axis of the crushing chamber. For a cone crusher the pivot point is above the mantle [63].

Pivot point placement for a cone crusher is shown in the following figure.

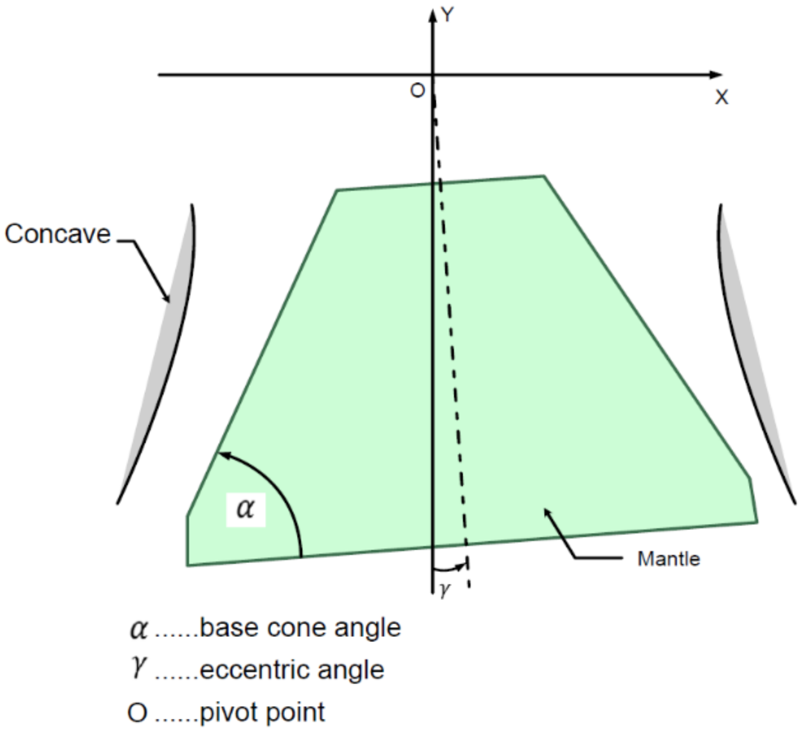


Figure 2.1.2.3 Pivot point represented for a cone crusher (figure is re-drawn inspired by [63]).

For a gyratory crusher, the pivot point is lower, on the mantle axis, on top of the moving mantle as can be seen in the following figure.

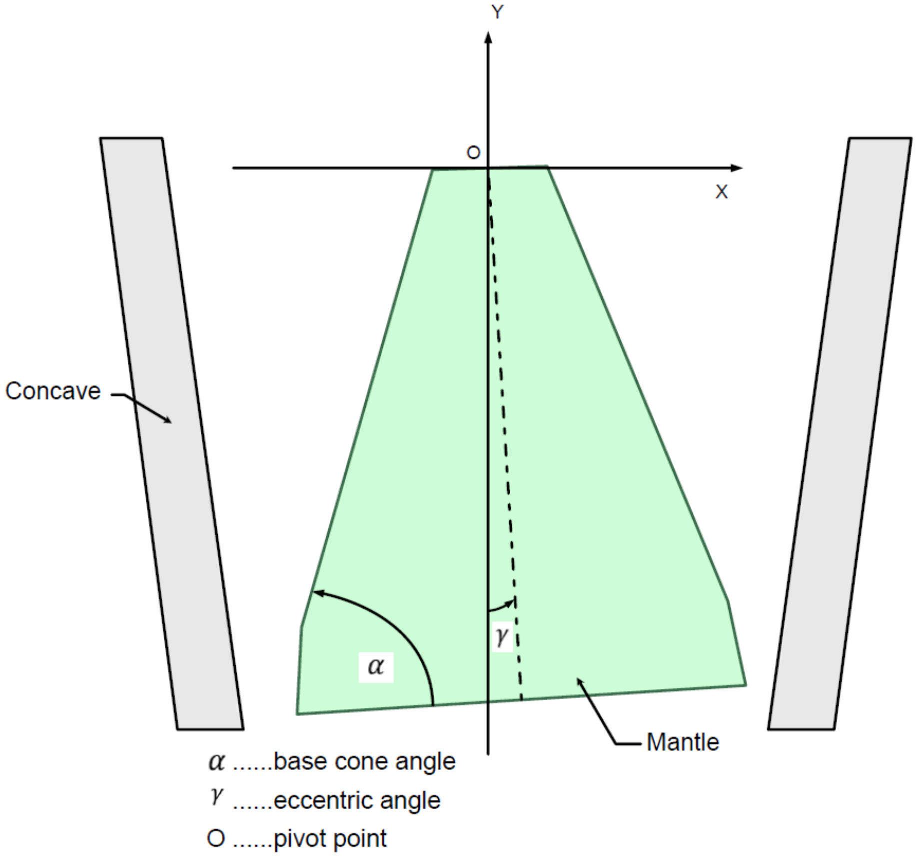


Figure 2.1.2.4 Pivot point for a gyratory crusher.

Impactive crushers:

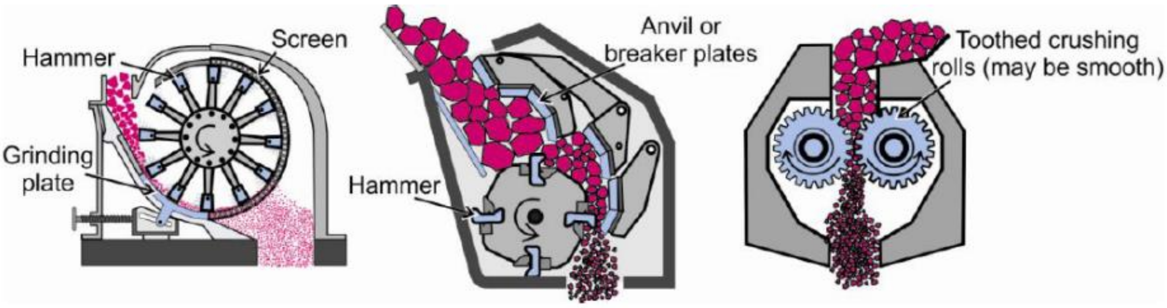


Figure 2.1.2.5 Impactive crushers examples, from the left: hammermill-type crusher, impact braker, roll crusher [62].

As the studied parts are components of cone crushers, only cone crushers are going to be elaborated in detail in the following chapter.

2.1.3 Cone crushers

Cone crushers are a type of compressive crushers that are used to crush aggregates or other material to smaller pieces. They are called cone crushers because a main mechanical part is cone shaped. It is a so-called cone head or simply head. The cone head is in eccentric rotational movement and moves a conic mantle attached to it. This conical mantel pushes the material against to a fixed bowl liner and therefore crushing it. The bowl liner and the mantle are both wear pieces – they are used over time and need to be replaced [65].

This basic principle of a cone crusher can be seen in the following two figures.

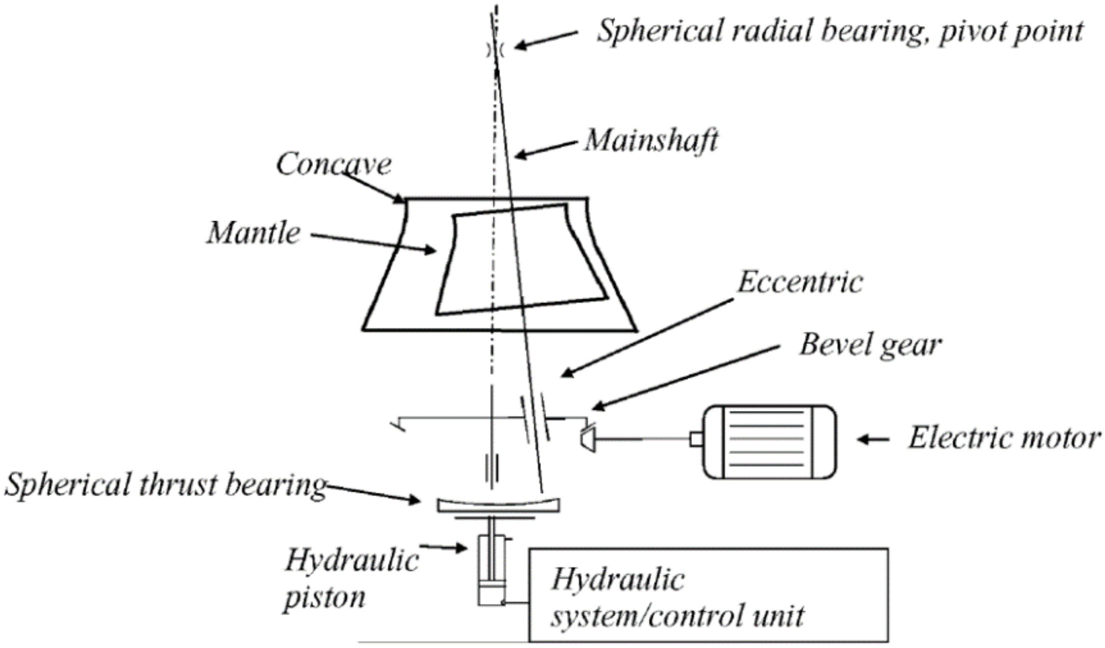


Figure 2.1.3.1 Schematic representation of cone crusher mechanics [65].

Example of a Metso cone crusher in section view with components designation can be seen in the following figure.

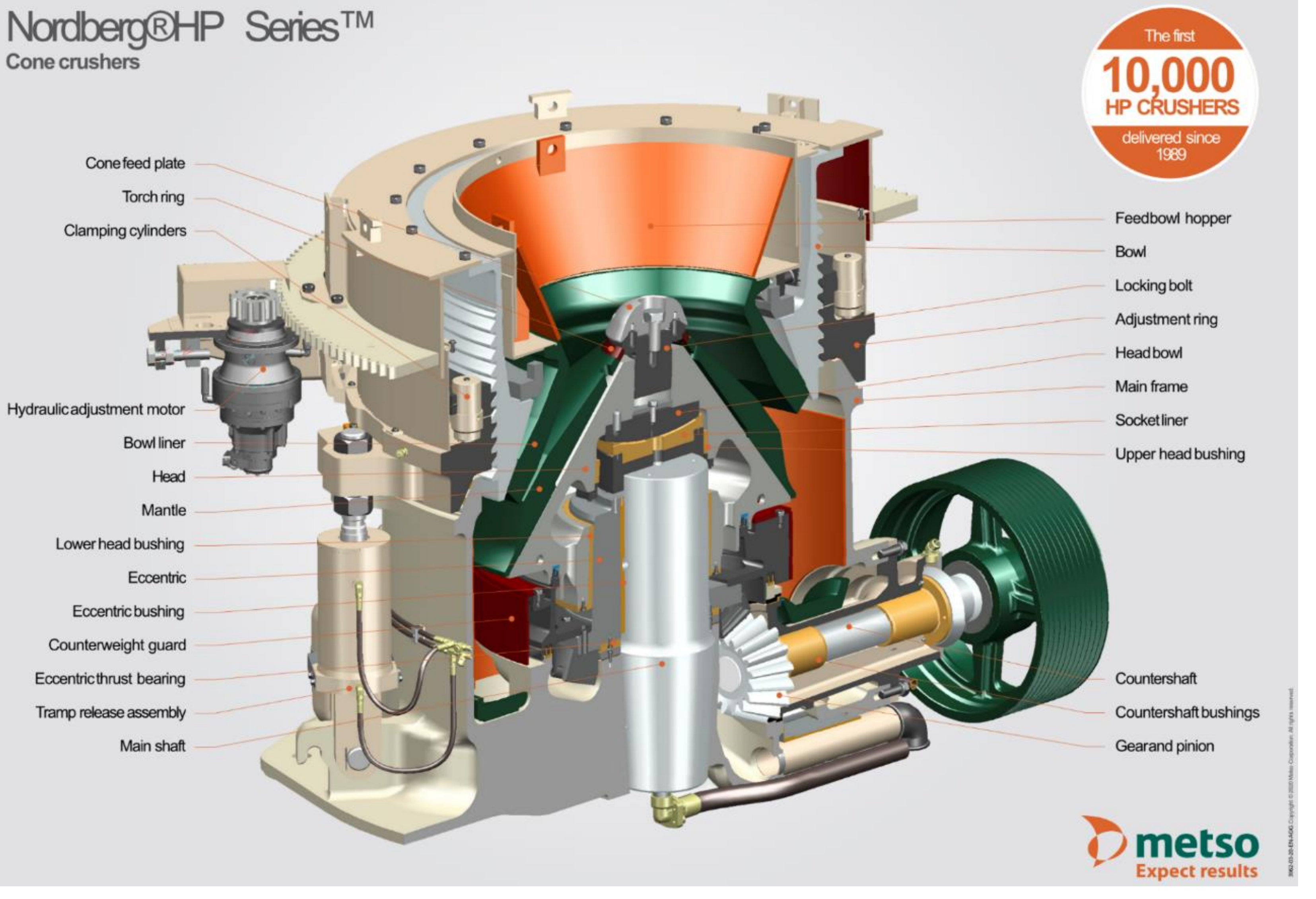


Figure 2.1.3.2 Metso cone crusher Nordberg® HP Series [66].

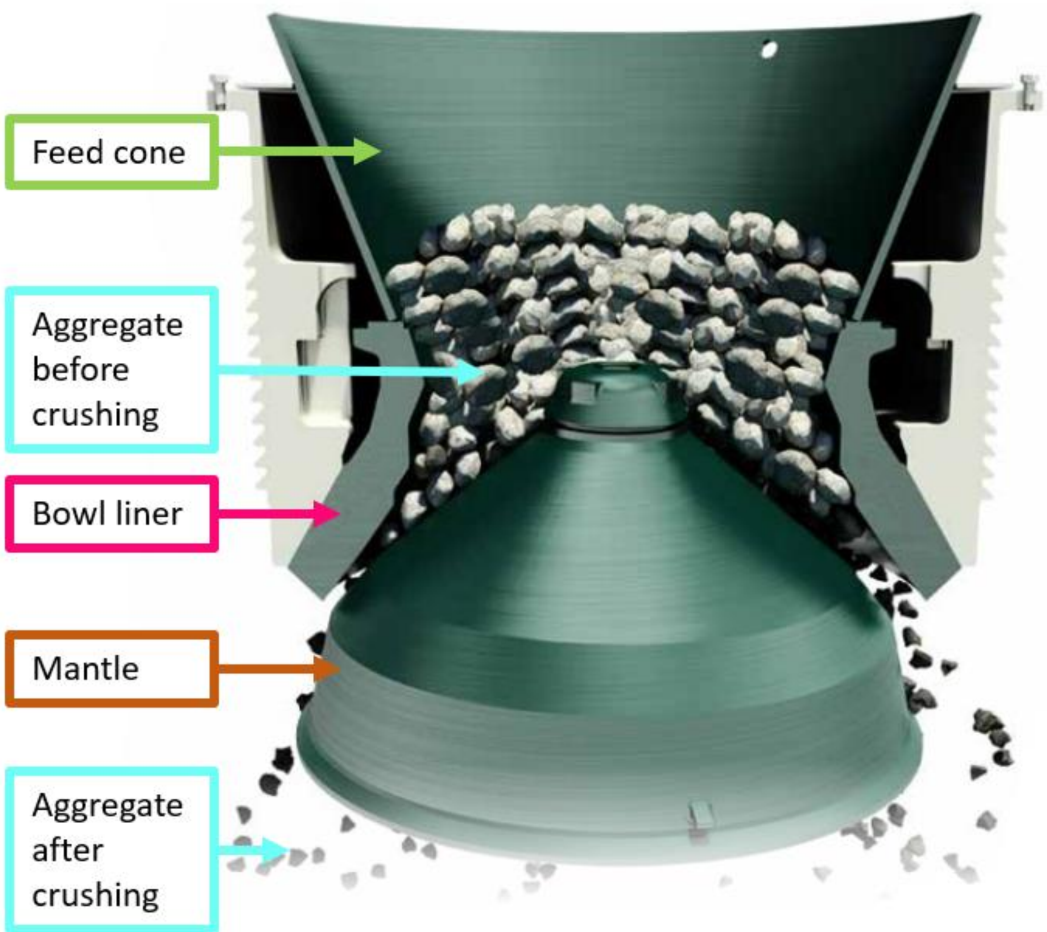


Figure 2.1.3.3 Cone crusher principle illustration [67].

The mantle and the bowl liner need to be changed when their wear reaches a certain value. Example of normal wear is shown in the figure below.

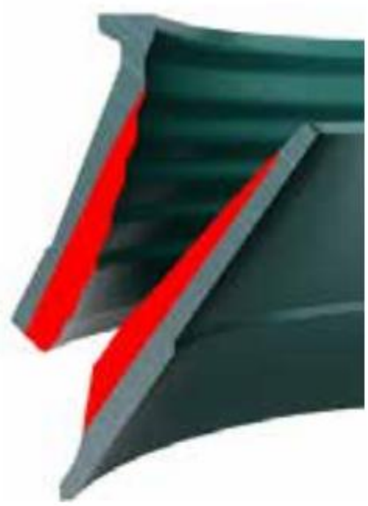


Figure 2.1.3.4 Normal wear of bowl liner and mantle [67].

There is usually one cone shaped fixed and one cone mantle moving eccentrically closing mantle attached to each cone together.

Metso fabricates many series of cone crushers. They are mostly used for crushing mined minerals (aggregates) but also for recycling purposes.

Metso families of stationary cone crushers are [68]:

- Nordberg® GP Series™,
- Nordberg® HP Series™,
- Nordberg® MP Series™,
- Metso MX™.

Examples of Metso cone crushers can be seen in the following figure:

Figure 2.1.3.5 Metso cone crusher, model MX3 in isometric view and section view [1].

2.2 STUDIED PARTS

The studied parts are head bolts, also called locking bolts or screw heads. The studied parts are a family of parts referred to as head bolts or screw heads or also locking bolts.

The head bolts are fabricated in small series depending on customer orders and rechange requests. In the future, recentralisation of fabrication of this family of parts is planned. All of this part may be fabricated at the company site in Mâcon. This would mean passing to medium size series while multiplying the original series size by two at least. Therefore, this study and future automation of the machine are even more important considering automation usually bring a considerate increase in productivity.

2.2.1 General machined part geometry

Precise dimension and tolerances of the studied part are confidential therefore cannot be presented. Only general geometry and approximate dimension are therefore presented.

The studied part in isometric view is shown in the following figure.

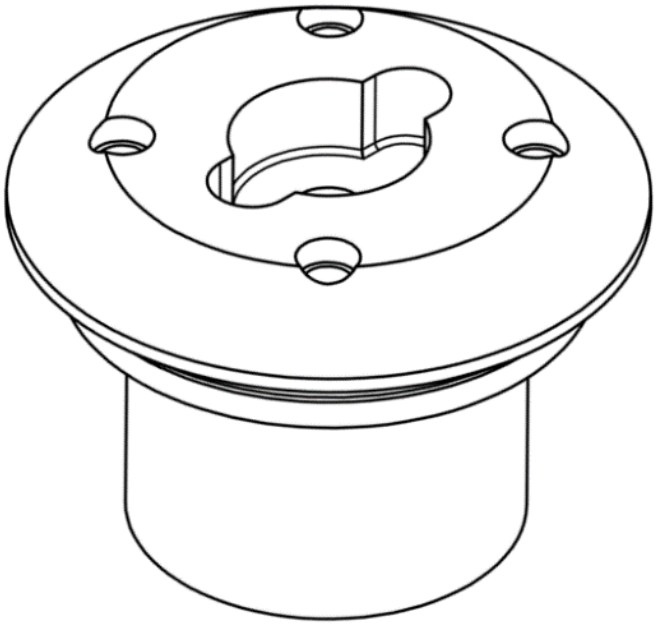


Figure 2.2.1.1 Studied part general geometry in isometric view.

General geometry of the studied part is represented in the following figure.

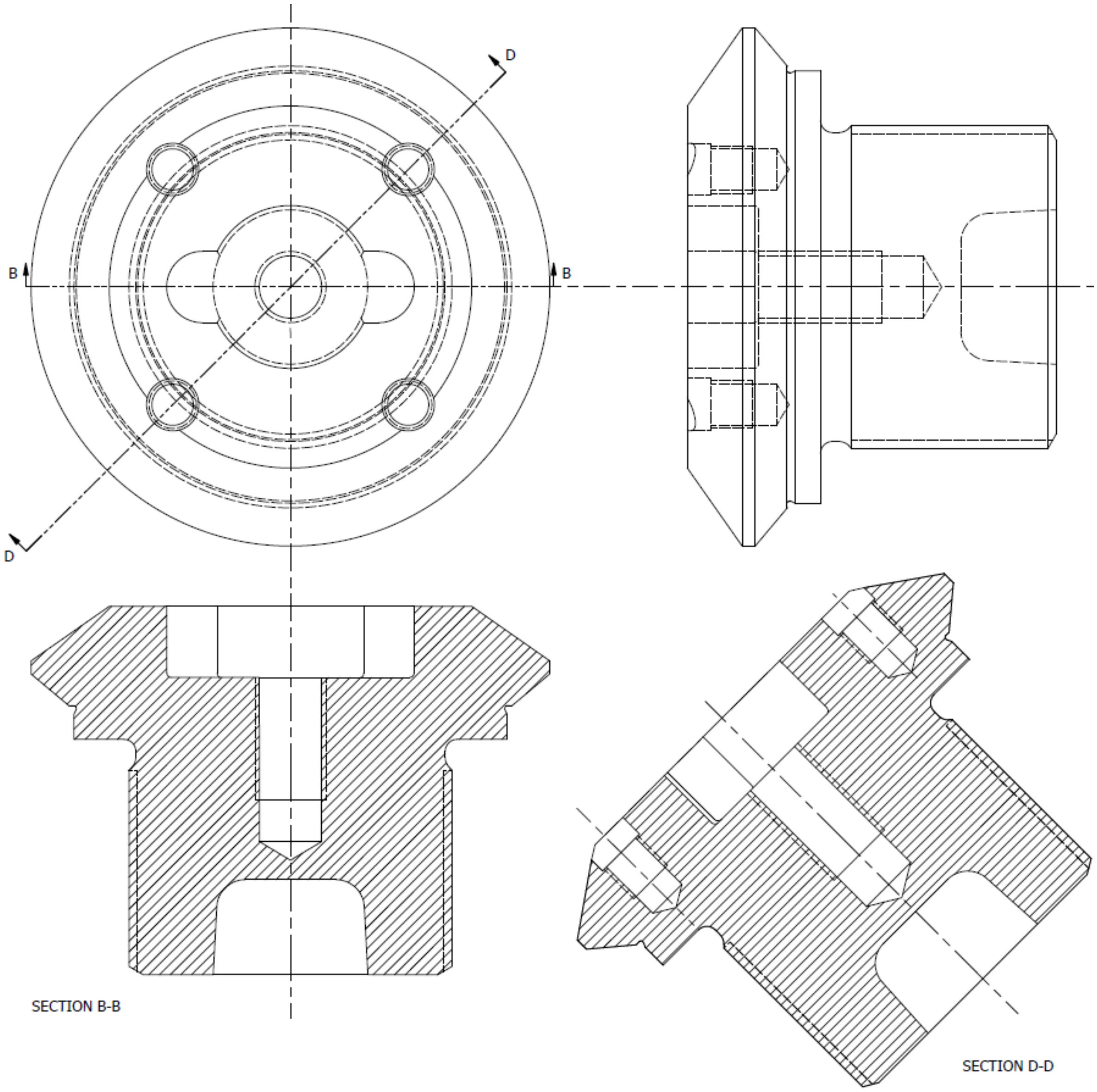


Figure 2.2.1.2 General geometry of a locking bolt for a Metso cone crusher.

There are differences of geometry between parts in the family of lock bolts. For example the number of threaded holes at the top vary; furthermore their diameters and the threads are different.

Head bolts also vary in sizes. Two parameters – maximum diameter and maximum length can be used to compare the different head bolts with each other. This illustrates the variation of size of those components.

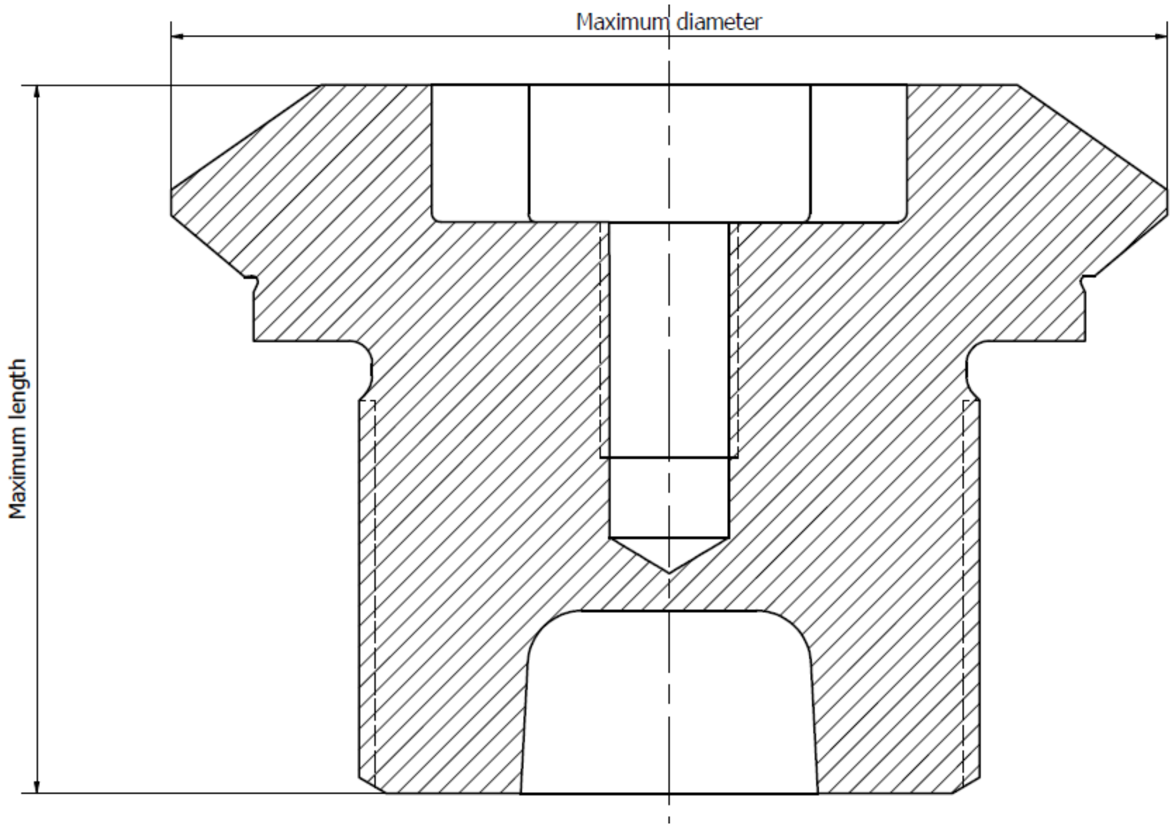


Figure 2.2.1.3 General geometry of a locking bot in section view.

Various sizes of locking bolts are listed in the table below.

Table 2.2.1.1 Ranges of maximum diameter and maximum length of the studied components.

Range of maximum diameter		Range of maximum length	
d_{min} (mm)	d_{max} (mm)	l_{min} (mm)	l_{max} (mm)
138	300	135	250

For example, various sizes of studied components are demonstrated in the figure below where the biggest locking bolt HP6 can be seen side to side with one of the smaller locking bolts – locking bolt HP3.

Figure 2.2.1.4 Difference of scale between two head bolts: HP6 (left) and HP200 (right).

2.2.2 Mechanical functions

The mechanical functions of the studied part can be concluded as:

- assembling the cone head (mechanical part of the crusher) and the mantle by a threaded joint,
- temporarily attaching a manipulation attachment to enable a sub-assembly manipulation.

The main mechanical function of head bolts is to attach the mantle of a cone crusher to the conic head. The head bolts create a sub-assembly of the mantle and the cone secured by the threaded joint between the head bolt and the cone head. The cone head is a mechanical piece and the mantle is a wear piece protecting the cone head. The head bolt has as well a protective wear piece attached to the piece, it is referred to as the cover cap or simply the cap.

The head bolt serves to create a link between the cone and the mantle. There is also an additional piece – a metal distancing ring placed between the mantle and the head of the locking bolt. The shaft is set in motion by a counter shaft which is set in motion by a motor with belt transmission. Between the shaft and the cone, there is an eccentric which ensures the eccentric rotation of the mantle. The sub-assembly composed of the cone head, mantle, distancing ring, head bolt and head bolt cover cap is in rotational movement.

Overall placement of the part in a cone crusher is shown in Figure 2.2.2.1.

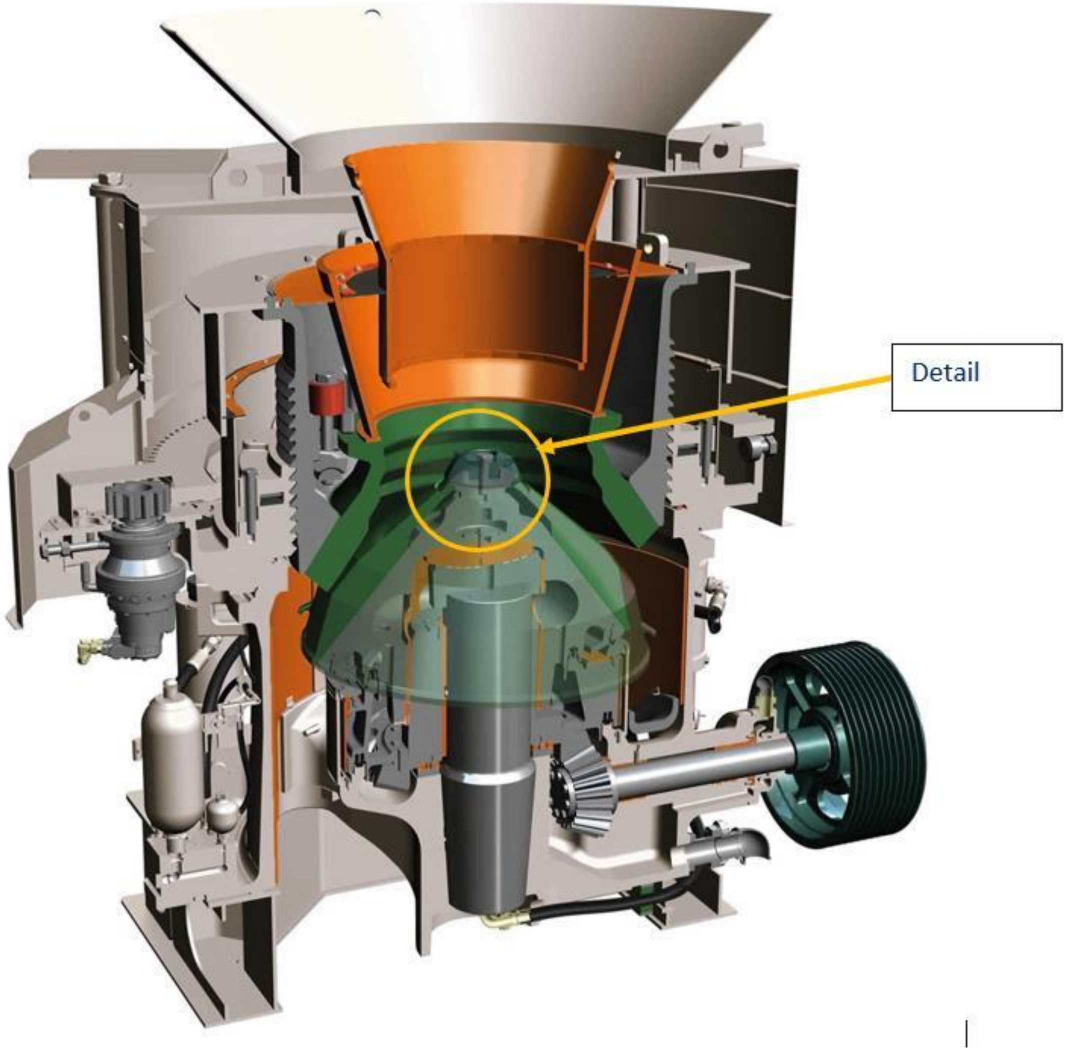


Figure 2.2.2.2 Placement of the studied part in a cone crusher in section view [69].

Detailed view of the component placement in the conical crusher is shown in the figure below.

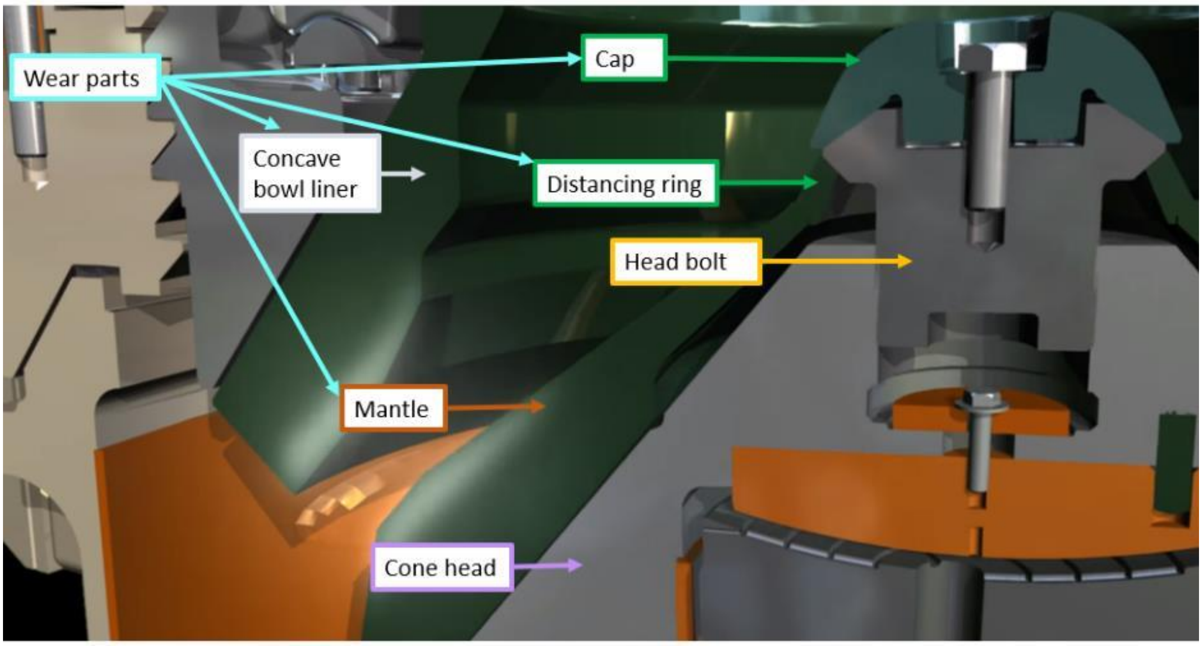


Figure 2.2.2.3 Detailed view of the part emplacement in section view.

2.2.2.1 Assembly

In a functional cone crusher, the locking bolt serves to connect the cone head with the mantle, but the locking bolt also has an important role during the assembly of the crusher. The whole sub-assembly is manipulated thanks to a manipulation attachment secured to the head bolt by four screws.

The second important role of the locking screw is during the assembly of the machine. The sub-assembly with the head, the bronze bushings and the movable jaw is held by a ring which is screwed by 4 screws in the locking screw. For the biggest cone crusher, this sub-assembly weighs about 5-6 tons. This sub-assembly is assembled and disassembled twice in the main assembly. The disassembly serves for checking the cone crusher’s functioning and safety, in the factory and after changing worn parts. Firstly, the machine is assembled and a short test run is performed. Then the sub-assembly is taken out and checked. If it passes the first test, the machine is submitted for a multiple-hour test run. After the long test run, once more the sub-assembly is taken out and it is inspected.

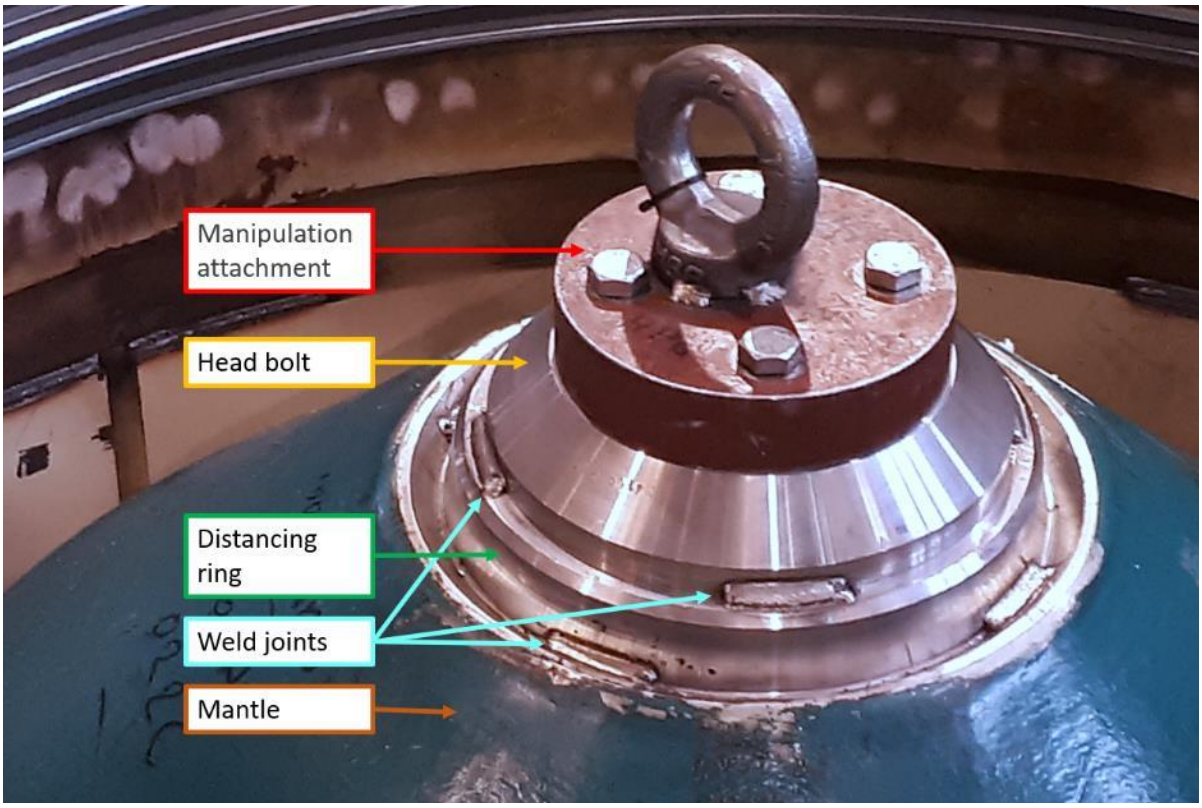


Figure 2.2.2.4 Head bolt placement during assembly of the cone crusher with manipulation attachment in place.

The head bolt is fastened to the cone head by a hydraulic wrench. The tightening torque is predefined for each crusher model. The hydraulic wrench has an attachment that is placed in the machined pocket of the locking bolt.

Before tightening the bolt, the bolt thread and the internal thread of the head must be deburred and ground to prevent gripping. Anti-gripping grease is applied on the whole thread.

For some models of cone crushers, the mantel is heated for the second stage of tightening. Heating is performed by flame, generally to about 80°C.

For each HP cone crusher model there are several types of mantels with various shapes, sizes and thickness for different crushing options.

There is sometimes a problem with loosening of the locking bolt.

The head bolt is welded in 4 places to the ring and the distancing metal ring is welded in four places to the head. All surfaces that are to be welded are degreased beforehand.

Placement of the studied part during assembly is shown in the following figure.

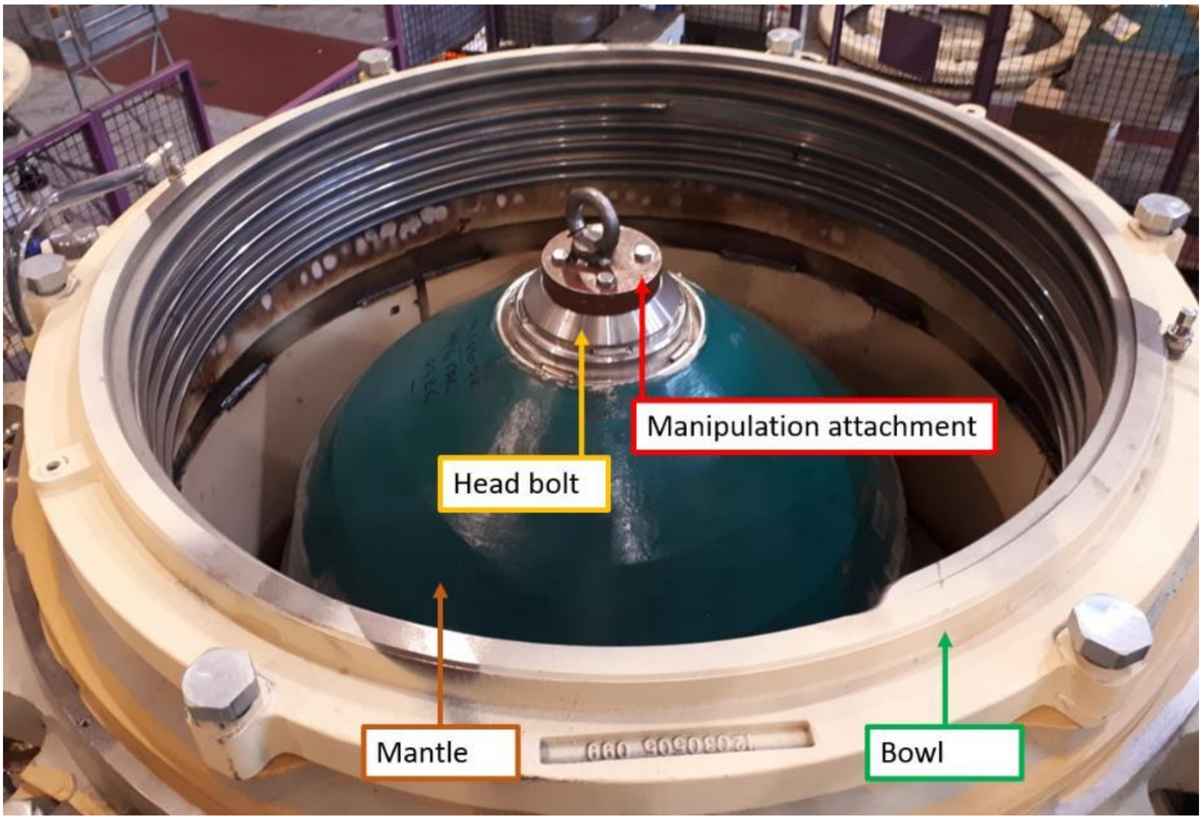


Figure 2.2.2.5 Placement of the head bolt during cone crusher assembly.

During assembly, the head bolt has an important role. Once the bolt screwed by a hydraulic wrench to the mantle (with a steel ring between them), and the joint is then welded

A manipulation attachment is then taken out and the wear piece called cap is mounted. The cap protects the locking bolt. The cap is attached to the locking bolt by a screw. The space between the screw and the cap is then filled with silicone to protect it from unfastening and damage by aggregates and dust particles. The subassembly completed by the cap is shown in the figure below.

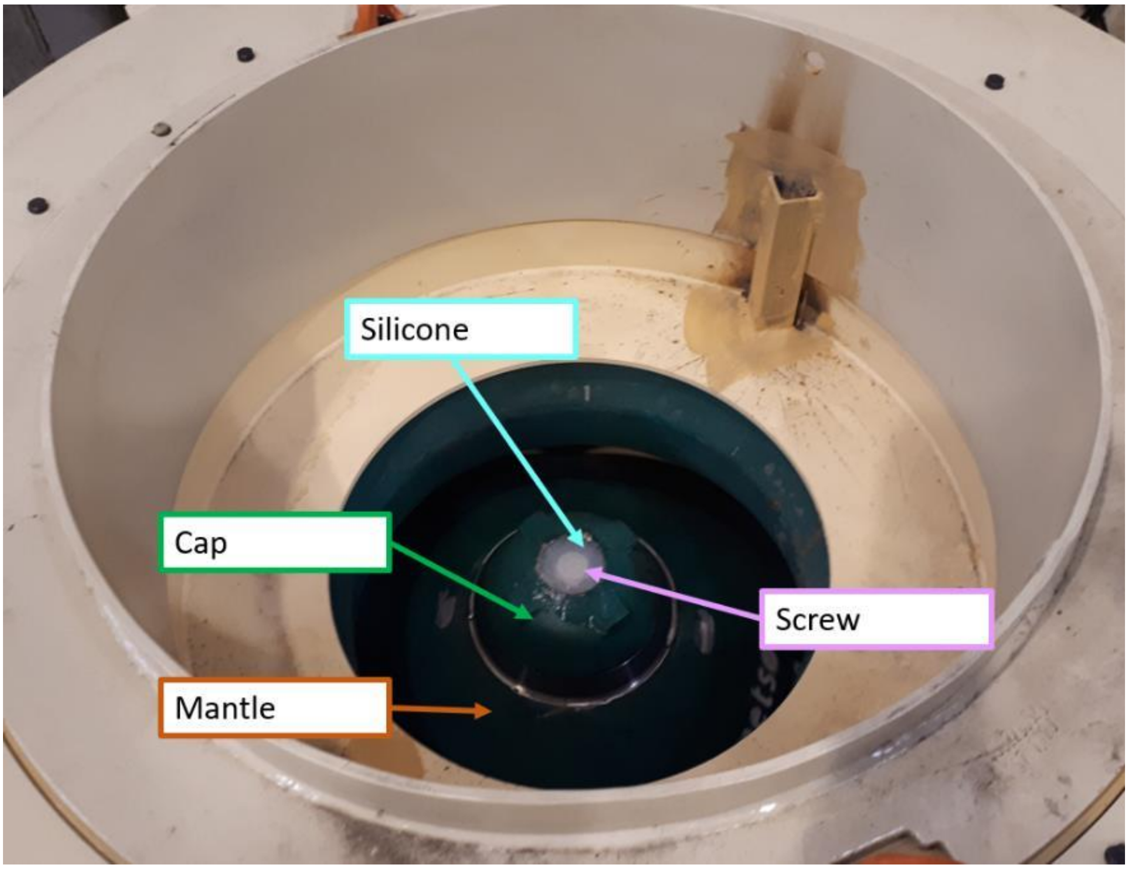
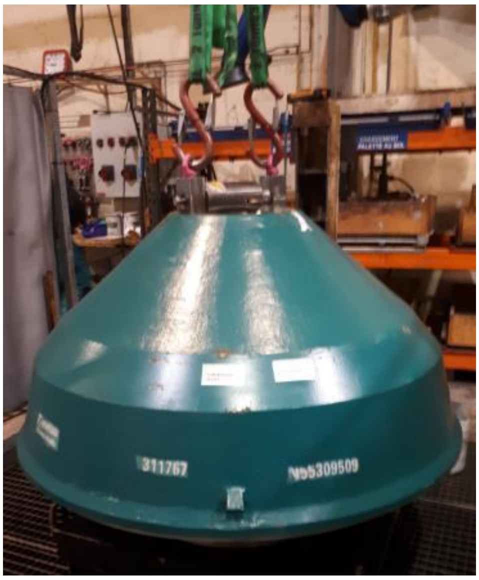
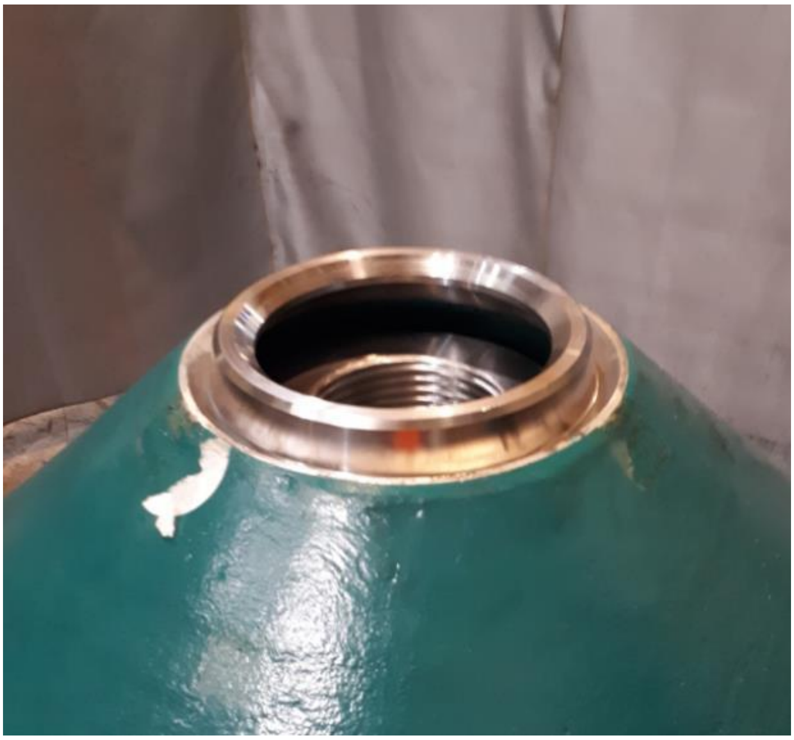


Figure 2.2.2.6 Head bolt covered with a wear cap and sealed by silicone during assembly.

Assembly process is shown on in the table below.

Step	Picture
Conical head before assembly	 
Mantel placement	 

Step	Picture
Head bolt manipulation and external thread grinding	 
Interior thread grinding	

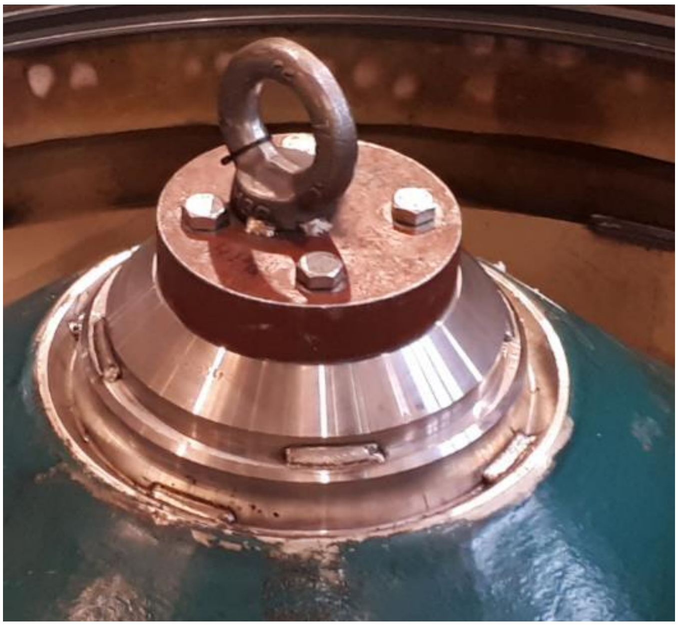
Step	Picture
Distancing ring placement on the mantel	

Step	Picture
Head bolt exterior thread preparation - grinding and anti-gripping grease application	
manual pre-fastening of the thread	

Step	Picture
hydraulic wrench set-up detail	
hydraulic wrench set-up	

Step	Picture
pre-fastened state	
after first fastening by a hydraulic wrench	

Step	Picture
heating of the mantle	
laser temperature measurement during heating of the mantle	 

Step	Picture
second fastening by a hydraulic wrench	
welded sub-assembly with manipulation attachment fastened by 4 screws	

Step	Picture
sub-assembly suspended by manipulation attachment	
sub-assembly manipulation	

Step	Picture
sub-assembly placement in the cone crusher	

2.2.3 Material

The studied parts are all from the same steel: 30CrNiMo8 + QT according to the norm NF EN ISO 683-2.

30CrNiMo represents the steel designation. It belongs to the category of low alloyed steels. This category of steels is more performant than carbon steels and it enables quenching of massive components, for 30CrNiMo quenching of large diameters (more than 200mm) is possible [6].

QT represents its heat treatment: quenched and tempered.

Steel 30CrNiMo8 is typically used for components: shafts, gears, rods, levers or nuts and bolts [6].

2.2.3.1 Chemical composition

According to the norm NF EN ISO 683-2, 30CrNiMo8+QT has following mass fractions of elements:

Table 2.2.3.1 Chemical composition of 30CrNiMo8 steel [70].

Steel designation	Elements (wt.%) limits according to NF EN ISO 683-2									
	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Fe
30CrNiMo8	0,26 to 0,34	0,10 to 0,40	0,50 to 0,40	0,025	0,035	1,80 to 2,20	0,30 to 0,50	1,80 to 2,20	0,4	balance

As the designation of the steel suggest, most important alloying are chrome, nickel and molybdenum. Ni, Mo and Cr increase the ability of the material to be quenched and increase the material hardness through forming hard precipitations [6].

2.2.3.2 Mechanical proprieties

For this material after heat treatment the norm dictated following mechanical properties for applied range of diameter of workpieces:

Table 2.2.3.2 Mechanical proprieties of steel 30CrNiMo8+QT [70].

Steel designation	Mechanical proprieties				
	for 160< d <250 or 100 < t < 160				
	minimal Rp0,2	**Rm**	**A**	**Z**	**KV**
	MPa		%	%	J
30CrNiMo8 + QT	750	930-1130	12	50	45

Hardness of the material can be estimated by translating the normed mechanical proprieties. Tensile strength R_m can give an approximate value of hardness. This conversion can be found in conversions charts. The limits of Rm = 930-1130 MPa can be approximated as 271 to 327 HB (Hardness of Brinell) considering using 10mm steel ball and 3000kg worth of penetration force [9].

Weldability (the ability of the material to be welded) is an important propriety. The studied parts are welded to another part during assembly. Material 30CrNiMo8+QT is considered weldable.

Machinability in heat treated state is not guaranteed by the norm NF EN ISO 683-2, machining of material 30CrNiMo is recommended before its heat treatment, in state soft annealed [71].

Machinability of quenched and tempered material is lower due to higher hardness [34].

Heat treatment after machining causes deformation of the workpiece. Second machining to correct this deformation after heat treatment is sometimes needed [34].

It is possible for a heat-treated steel to still have good machinability.

The company chose to machine after the heat treatment of the material because it still has acceptable machinability.

2.2.4 Workpieces

Workpieces are cylindrical hot rolled rounds of different diameter and length for every screw head. Their dimensions can be found in the following table.

Table 2.2.4.1 Sizes of workpieces for different cone crushers.

Type of workpiece	Diameter (mm)	Length (mm)
HP100	150	145
HP200, MC200A	230	140
HP3	250	170
HP300, MC300A	250	170
HP4	250	187
HP400, MC400A	230	163
HP5	250	225
HP500	340	186
HP6	310	257

Because of the method of fabrication – hot rolling – there is an oxidized layer on the cylindrical surface. This layer is significantly harder than the rest of the workpiece. When machining this outer layer, it is important to increase the depth of cut ap in order to cut underneath this layer and avoid decreasing the tool life due to wear.

An example of workpieces used is shown in the figure 2.2.4.1, a brown crust of oxidized layer can be clearly seen.

Figure 2.2.4.1 Examples of workpieces.

Roughing of the surface layer must be adapted. A greater depth of cut should be used as is shown in the figure below.

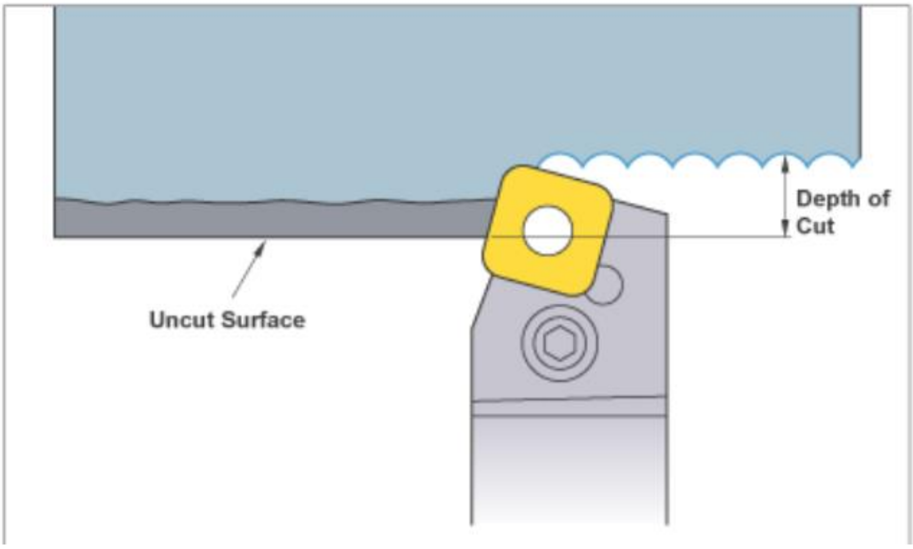


Figure 2.2.4.2 Depth of cut for roughing of part with uncut surface. [72]

This layer combined with a deviation of cylindricity poses difficult conditions for machining the first pass in roughing.

Figure 2.2.4.3 Workpiece with oxidized crust

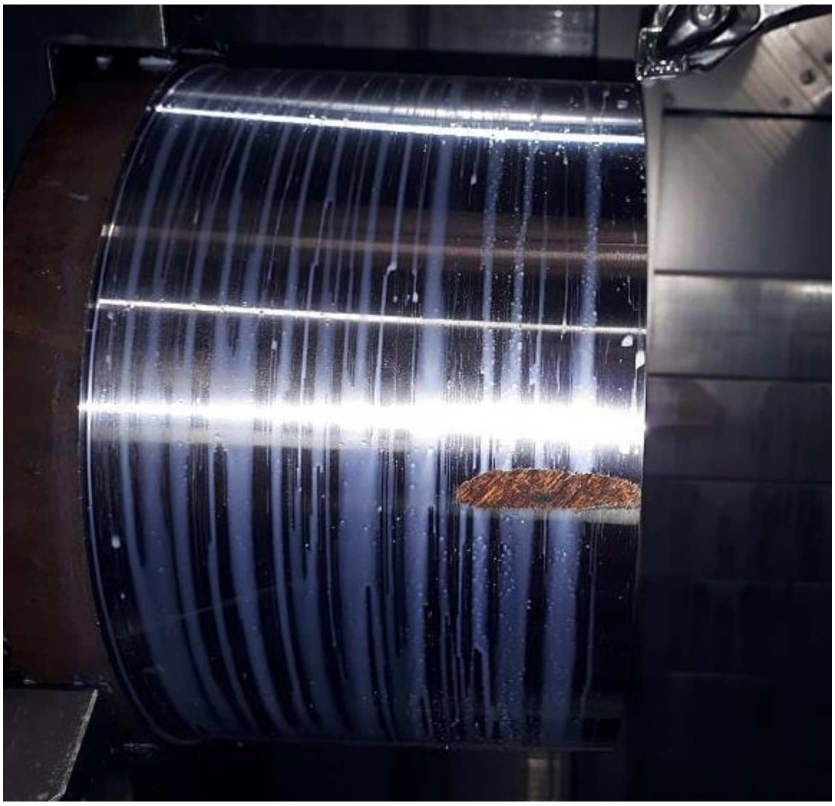


Figure 2.2.4.4 Significant flaw in cylindricity on a workpiece causing shocks during roughing of the external diameter.

2.2.4.1 **Workpiece manipulation**

The operator manipulates the workpiece using custom made jig that is different for every locking bolt. It attaches to the head of the locking bolt and is lifted by a crane.

Figure 2.2.4.5 Manipulation jig attached to a crane.

2.2.5 Functional and non-functional machined elements

Functional and non-functional elements can be distinguished on locking bolts.

Functional machined elements are:

- external thread,
- small threaded holes,
- central threaded hole,
- top pocket.

Non-functional machined elements are:

- groove,
- bottom pocket.

2.2.5.1 External thread

External thread is the main functional element of locking bolts. It is the surface that ensures the main function of the locking bolt – creating an assembly by a threaded joint.

This element of external thread is represented in the following figure.

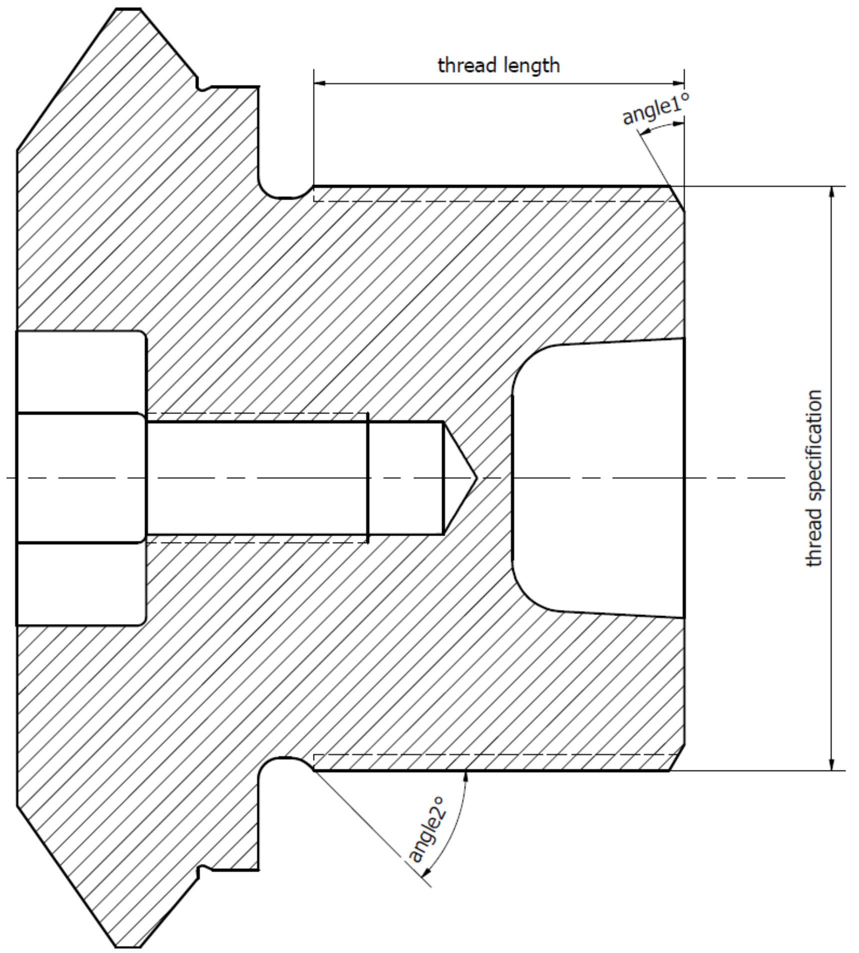


Figure 2.2.5.1 External thread element.

Dimensions variation of the external thread is in the following table.

Table 2.2.5.1 Different external threads of locking bolts.

Thread specification	Thread length (mm)	angle1 (°)	angle2(°)
M130x6-6g-LH	61	30	45
M140x8-LH-6g	86	30	45
M150x6-LH-6g	81	30	45
M160x6-LH-6g	96	30	45
M180x6-LH-6g	71	30	45
M170x8-LH-6g	106	45	45
M200x6-6g-LH	75	30	45
M200x12-6g-LH	145	30	45

The groove linked to angle2° after the thread has an important role to enable thread turning and leaves vacant space to which the thread turning tool can enter safely when finishing the thread turning.

2.2.5.2 **Groove**

Just behind the external thread there is a groove. It has parameters as presented in the following figure.

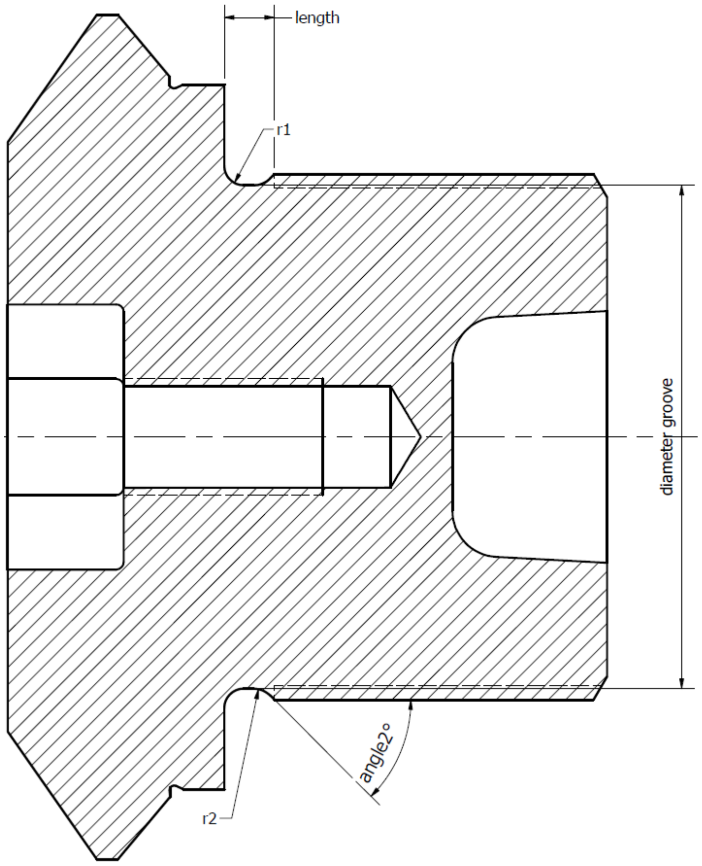


Figure 2.2.5.2 Parameters of the groove on a drawing of a locking bolt.

The parameters of the groove have following ranges of values for different locking bolts:

Table 2.2.5.1 Range of groove dimensions.

Range of groove diameter		Range of length of the groove		Range of radius 1		Range of radius 2	
d_{min} (mm)	d_{max} (mm)	L_{min} (mm)	L_{max} (mm)	$r1_{min}$ (°)	$r1_{max}$ (°)	$r1_{min}$ (°)	$r1_{max}$ (°)
90	180	12	57	2	5	5	10

The groove has two meanings:

- leaves space for thread turning tool to safely leave the material during cutting
- introducing a radius instead of steep angle that would be prone to fatigue cracking.

The surface of the groove is not a functional surface.

2.2.5.3 **Small threaded holes**

On the face of the head of locking bolts there are small threaded holes. These threaded holes are used to attach the manipulation attachment during assembly. The multiple ton subassembly is then suspended by the attachment. These threaded holes are functional and important during the assembly process and during change of wear components of the cone crusher on client’s work site.

These small threaded holes are displayed in the figure below

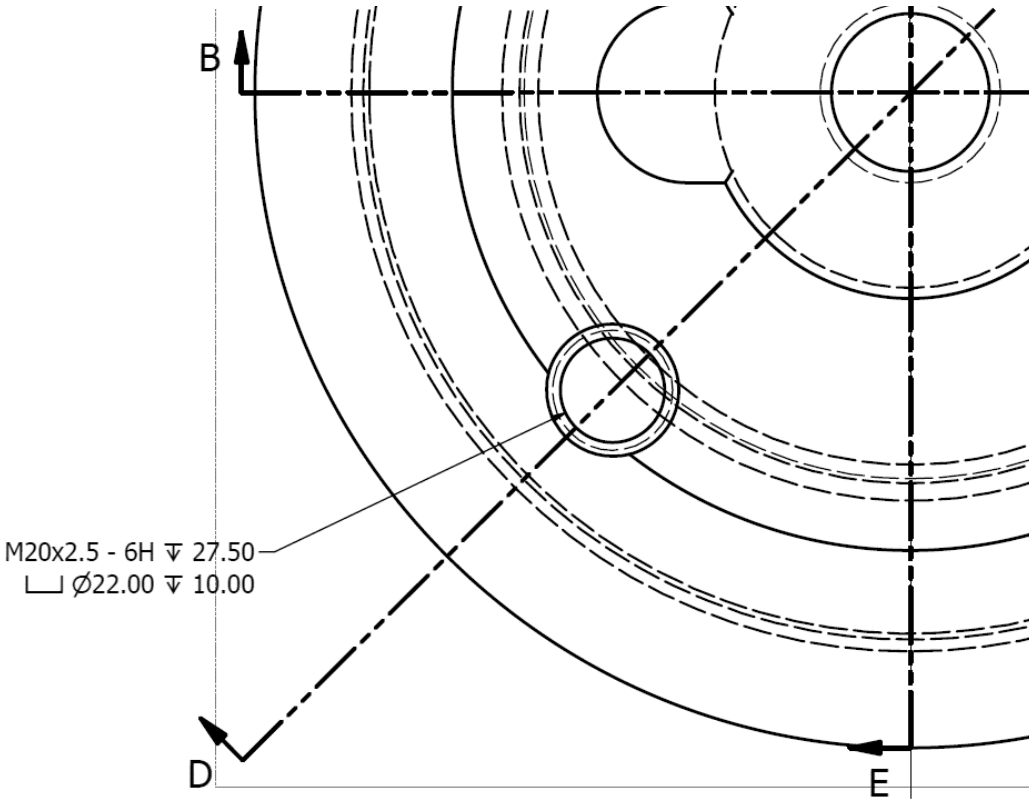


Figure 2.2.5.3 Small threaded hole on the head of a locking bolt.

The small threaded holes can be seen also in section view D:

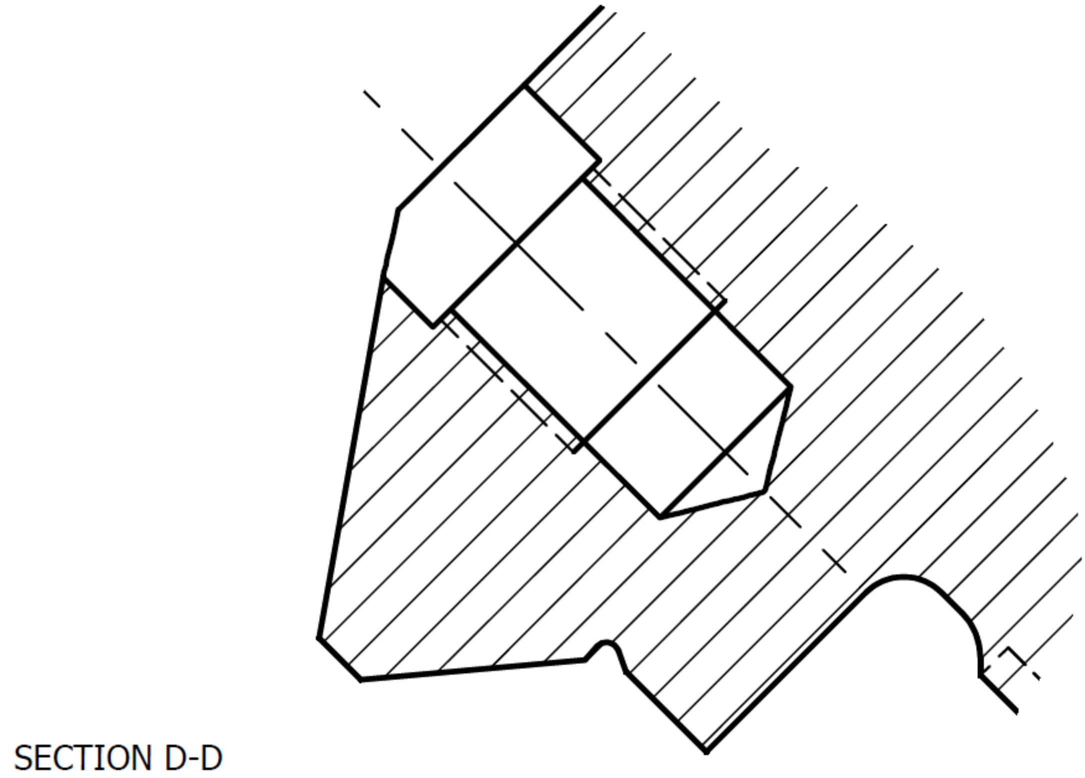
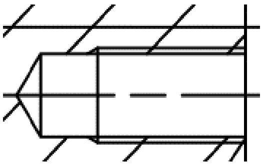
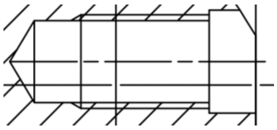
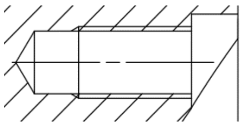
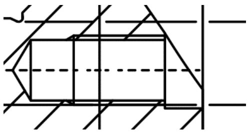
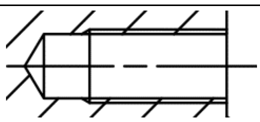
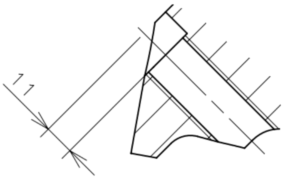
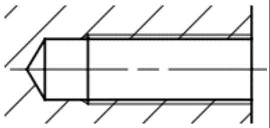
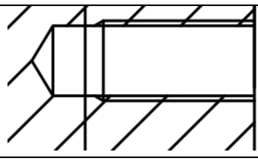


Figure 2.2.5.4 Small threaded holes in section view D.

The small threaded holes can be of different parameters and counterbored or not and have different threaded lengths Two types of threads can be differentiated: M16x2-6H

Table 2.2.5.1 Threaded holes specification for small threaded holes on the face of the locking bolt.

Thread	Threaded hole drawing	counterbore diameter (mm)	counterbore depth (mm)	length of thread (mm)	Max. mill length engaged (mm)
M16x2-6H		0	0	26	26
M20x2,5-6H		22	10	27.5	37.5
M16x2-6H		22	10.5	25.5	36
M20x2,5-6H		22	11	26.5	37.5
M20x2.5		0	0	37,5	37,5
M20x2,5-6H		22	11	36	47
M20x2,5-6H		0	0	47.5	47.5
M20x2,5-6H		0	0	37.5	37.5

2.2.5.4 **Central threaded hole**

Locking bolts have a central threaded hole that is used to attach the wear component to the head of the locking bolt when it is assembled in the conical crusher. This machined element is therefore functional.

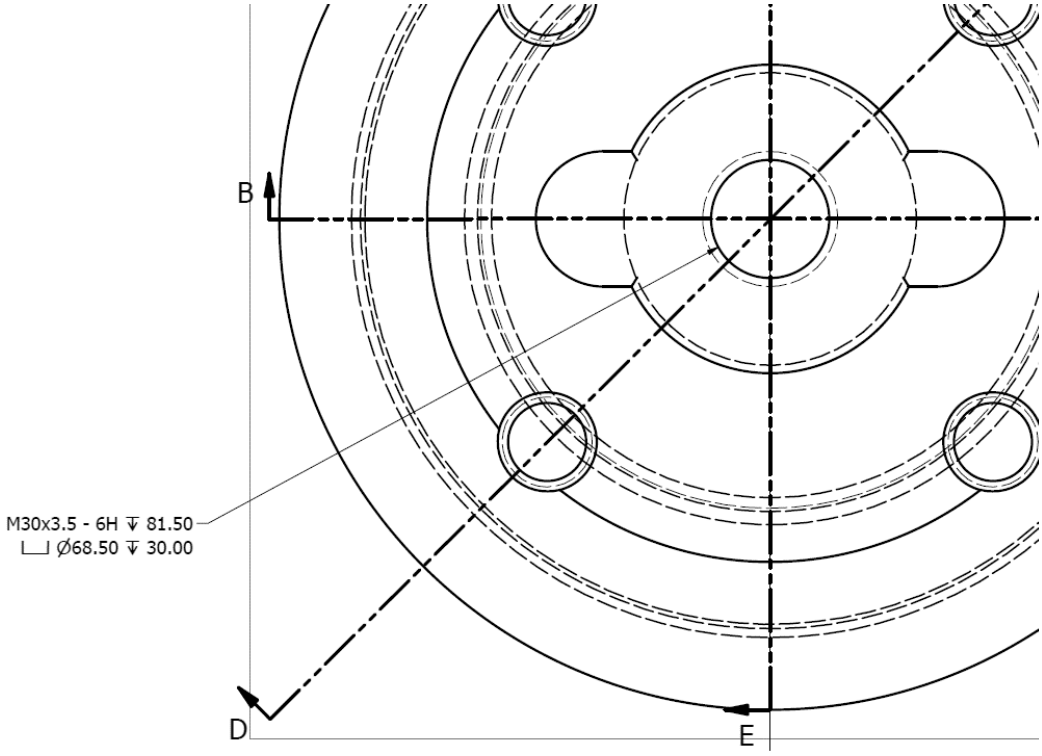


Figure 2.2.5.5 Placement and example of dimension of the central threaded hole on a locking bolt.

Different specifications and their ranges for the central threaded hole are listed in the table below.

Table 2.2.5.2 Different central threaded hole specifications on locking bolts.

General information			Range of threaded length		Range of counterbore depth		Range of counterbore diameter	
Thread	D nominal (mm)	Pas	L_{min} (mm)	L_{max} (mm)	l_{min} (mm)	l_{max} (mm)	$d_{c, min}$ (mm)	$d_{c, max}$ (mm)
M30x3,5-6H	30	3.5	50	51.5	30	31	68	155
M42x4,5-6H	42	4.5	61.5	87.5	30	42	68.5	155

The counterbore in the case of the central hole represents the turned diameter of the pocket at the face of the locking bolt. It is important to know the counterbore to make sure the tool used for machining of the thread is not in risk of collision with the material of the counterbore.

2.2.5.5 **Pocket on the bottom face**

On the downside, of the locking bolt, there is a conical pocket. It is not a functional surface ad serves to make the locking bolt lighter and the external thread more flexible. This feature is not present on all locking bolts. The pocket is machined by drilling followed by turning.

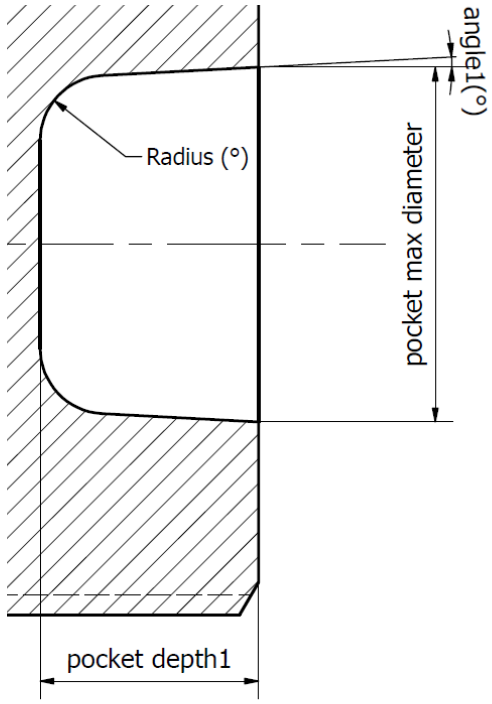


Figure 2.2.5.6 Dimension of pocket on the bottom side of a locking bolt generally described.

Different dimension of the pocket are featured in the table below.

Table 2.2.5.3 Different dimension of the bottom side of locking bolts.

	Radius (mm)	Pocket depth1 (mm)	angle 1 (°)	Maximum diameter (mm)
HP200	X	X	X	X
HP3	12	40	3	65
HP300	X	X	X	X
HP4	5	28	3	80
HP400	X	X	X	X
HP5	20	50	10	92
HP500	X	x	X	X
HP6	20	65	3	110

2.2.5.6 **Pocket on the top face**

Pocket on the top face of the locking bolt serves during assembly to attach the hydraulic wrench during tightening of the locking bolt.

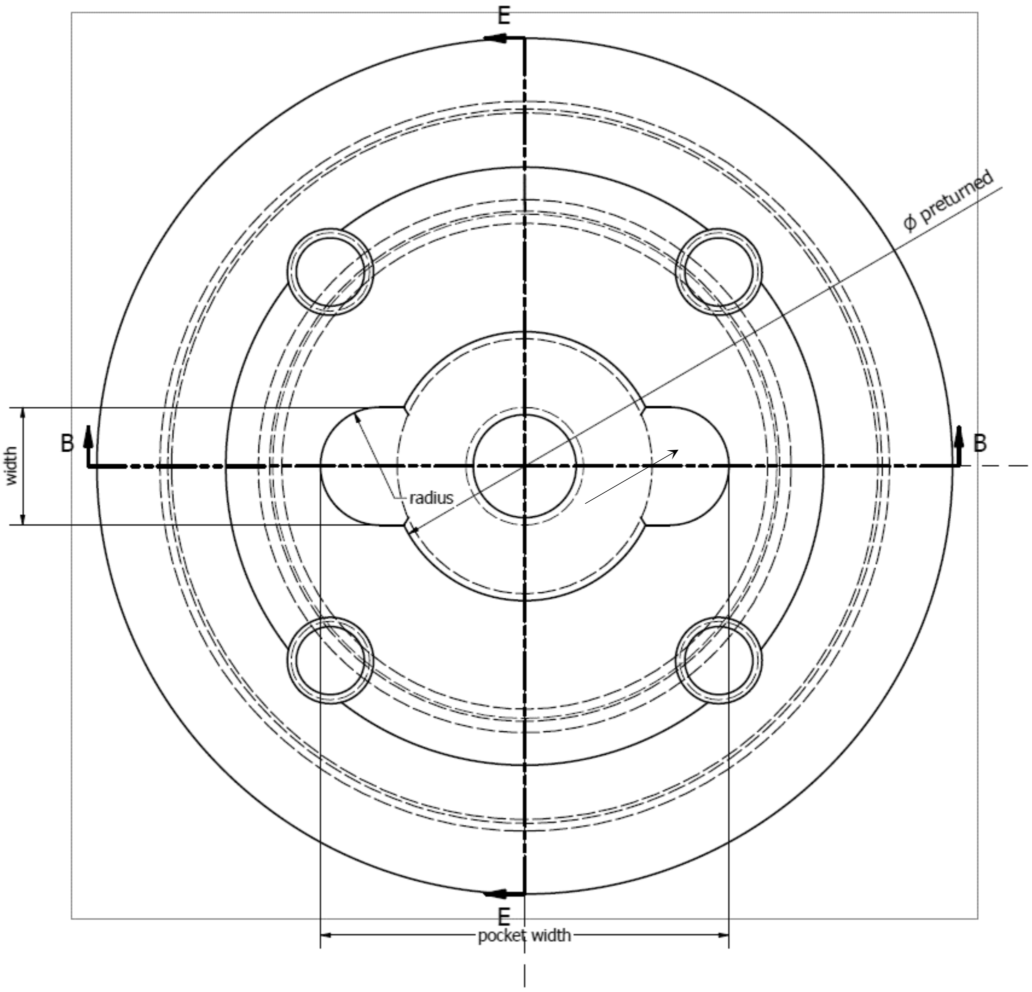


Figure 2.2.5.7 Dimension of the top machined pocket.

Ranges of dimensions of the top pocket are listed in the table below.

Depth of the pocket is always either 30 mm or 42 mm.

Table 2.2.5.4 Parameters of the top pocket.

Number of slots	Range of slot width		Range pocket width		Range of radius		Range of preturned diameter	
n_s	w_{min} (mm)	w_{max} (mm)	W_{min} (mm)	W_{max} (mm)	r_{min} (mm)	r_{max} (mm)	d_{min} (mm)	d_{max} (mm)
0, 2, 4	30	40	108	160	15	20	68.5	91

2.3 MACHINE USED FOR MACHINING OF THE STUDIED PART

The machine used to fabricate the studied part is NT 4250 DCG Turn & Mill machine by DMG Mori. This machine can be classified as multifunctional lathe which means that its main function is a lathe but it can perform milling operations too thanks to a milling spindle while the turning spindle is blocked to maintain the workpiece in position.

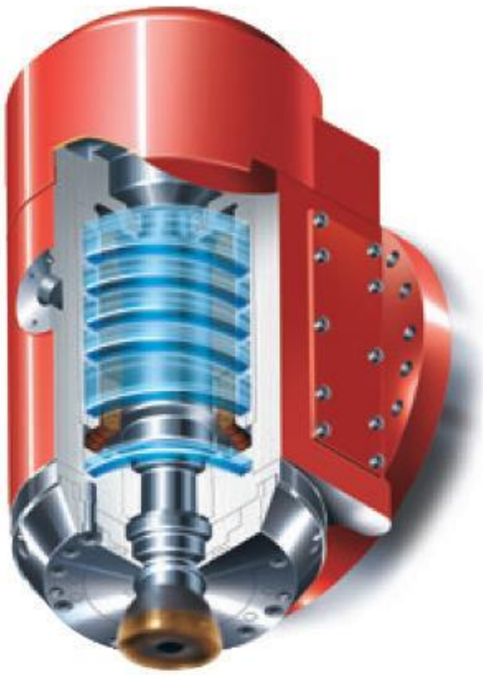


Figure 2.3.1 Tool spindle of NT 4250 DCG Turn & Mill CNC machine enabling use of rotational tools, cooling of the spindle in section view.

The NT series has four machine sizes: 4200, 4250, 4300 and 5400 with corresponding chuck sizes: 8 inches, 10 inches, 12 inches and 15 inches. NT 4250 is the second smallest with chuck size of 10 inches.

Figure 2.3.2 NT 4250 DCG Turn & Mill machine at Metso workshop with smaller locking bolts.

Interior of the machine with chucks attached to both spindles is displayed in the figure below.

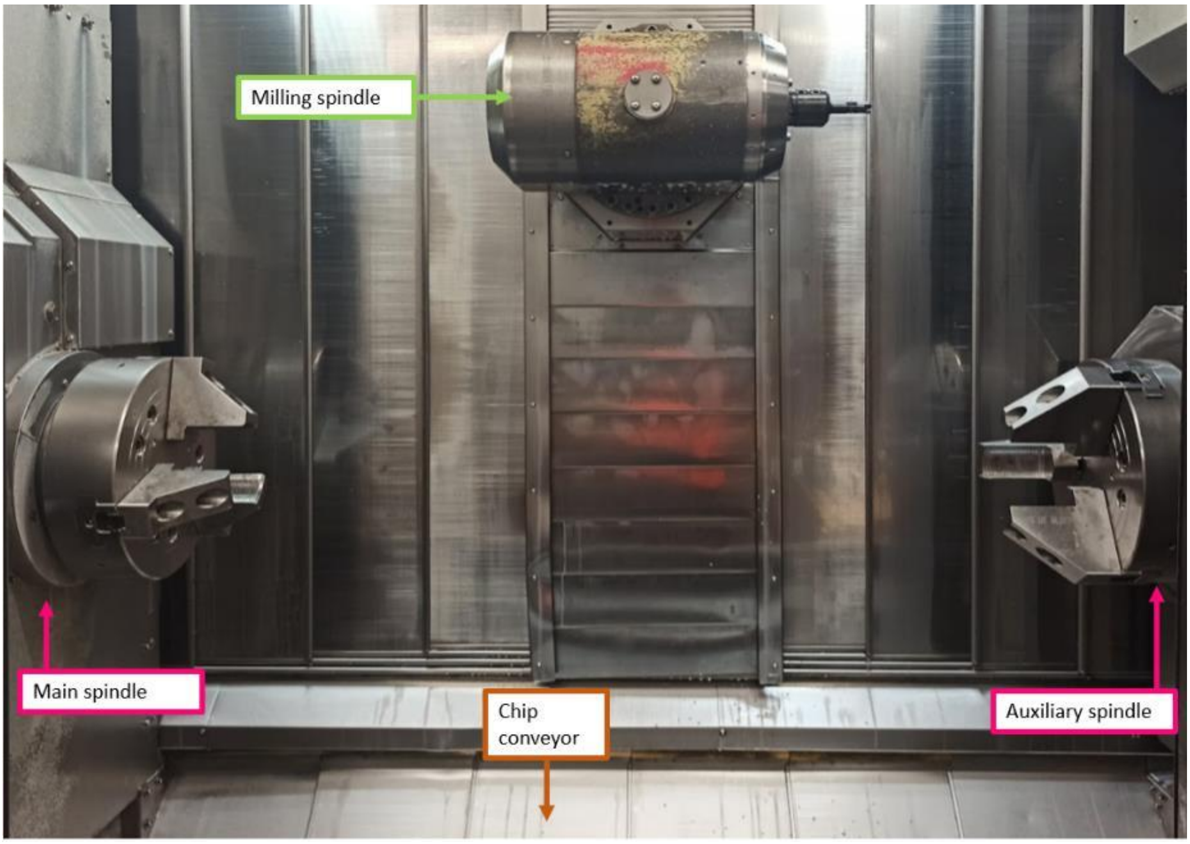


Figure 2.3.3 Interior of NT 4250 DCG Turn & Mill CNC machine at Metso.

The machine uses ISO tool attachment system Capto (size C6).

The spindle is an electric spindle. The machine does not have a gear box. Electric spindle and absence of a gearbox implies low limit of torque available and causes a fragility of the machine.

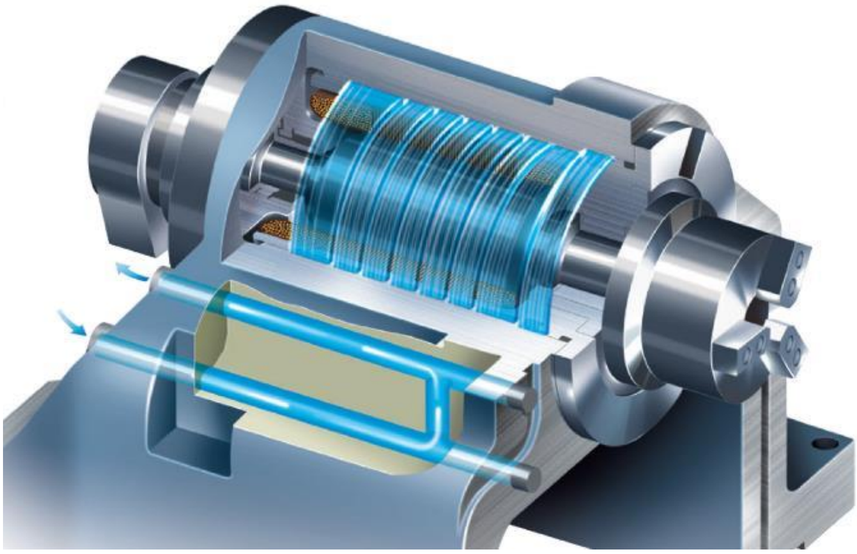


Figure 2.3.4 Electric spindle with cooling system shown in section view [73].

2.3.1 Machine characteristics

The NT 4250 DCG Turn & Mill machine is a 4-axis machine. Its structure can be described as RTTT (axis B rotation, axis Y translation, X translation, Z translation when going from the tool to the workpiece).

The machine has two synchronised spindles with rotations C1 and C2. Axis X2 and Z2 and A can also serve for workpiece transfer between the two spindles thanks to the synchronisation of spindles. A counterpoint can also be mounted manually in chuck of one of the spindles (usually the auxiliary spindle).

Structure of the machine is shown in the figure below

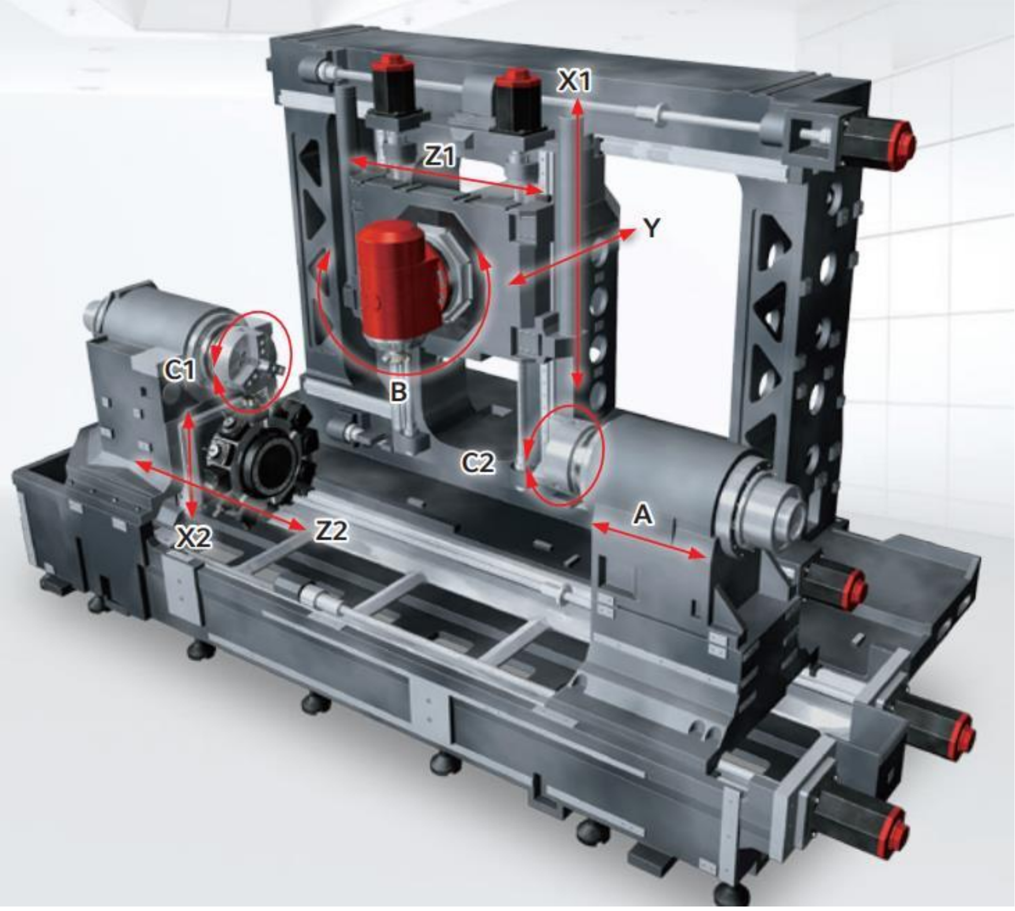


Figure 2.3.1.1 Axis of NT 4250 DCG [73].

The basic characteristics of the machine are listed in the following table:

Table 2.3.1.1 Characteristics of NT 4250 DCG machine at Metso workshop [73].

Characteristics			
Max. diameter allowed above the bench	730	mm	
Max. length between centres	1862	mm	
Max diameter - swing over cross slide	750	mm	
Courses			
X axis course	750	mm	
Y axis course	210	mm	
Z axis course	1635	mm	(+100 for ATC)
B axis course	±	mm	indexable for all degrees
Rapid traverse speed			
Axes X et Z	50	m/min	
Axe Y	30	m/min	
Axe B	40	1/min	
Axe C	400	1/min	
Spindle - turning (main and auxiliary spindle)			
Max. rotation speed	4000	rot/min	
C Axis , Power max. for 30 min	22	kW	
C Axis , Power	18.5	kW	
Milling spindle			
Max. rotation speed	12000	rot/min	Capto 6
Power max. for 30 min	18.5	kW	
Power	11	kW	
Tool change time	1	s	
Other			
Weight	24300	kg	
Equipment			
Chuckles	381	mm	on main and auxiliary
Coolant pressure - centre of milling	15	bar	

The machine at the Metso workshop was installed in 2003.

2.3.2 Machine equipment

The used machine has FANUC control system and has Mapps II software interface. FANUC programming language was presented in the theoretical part.

The machine is equipped by a coolant by centre of milling tools and an external coolant with maximum pressure of 15 bars. The cutting fluid is imposed by the workshop as 5% emulsion.

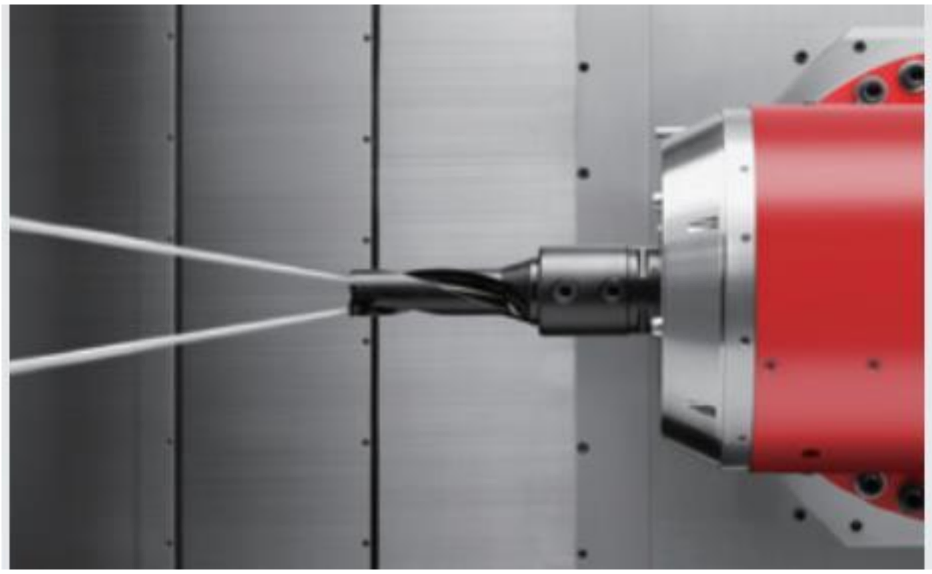


Figure 2.3.2.1 Cooling system of the NT 4250 DCG machine [73].

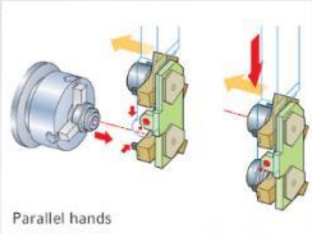
2.3.2.1 Tool changer and magazine

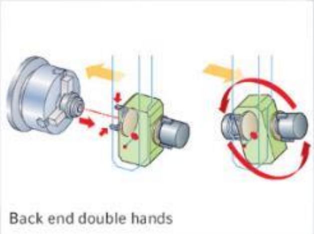
The machine is equipped with an ATC – automatic tool changer. It can contain more than 100 turning tools. Time of tool change is $t_c = 1$ s if the tool is called in advance in the program so the machine prepares it to be loaded. This is a quick tool change which allows many tool changes without risking machine time to be prolongated much by using many tools.

2.3.2.2 Machine automation solutions

The fabricant of the machine offers automation solutions such as bar feeder system and gantry-type loader systems. Nevertheless, these solutions for workpiece feed are limited and unusable for the majority of studied workpieces due to their large dimension.

Gantry-type loader system (Option) <Consultation is required>





Gantry loader standard accessory / specification

- 10-station rotary workstocker (LG-10)
- Hand airblow
- Chuck air-blow
- Automatic power-off system
- Workpiece counter (PC counter)
- Spindle orientation
- Low air pressure detecting switch

For these models
NT4200 DCG NT4250 DCG NT4300 DCG

				LG-10 (machine travel type
Gantry loader	Max. travel speed	X-axis <Hand moves up and down>	m/min (fpm)	90 (295.3)
		Z-axis <Loader moves right and left>	m/min (fpm)	120 (393.7)
Work stocker	Applicable workpiece size	Outer diameter	mm (in.)	ϕ 40−200 (ϕ1.6−7.9)
	Number of pallet tables			10 [20]
	Max. loading capacity		kg (lb.) / Pallet	75 (165)
	Max. workpiece stacked height		mm (in.)	470 (18.5)
Loader hand	Hand type			Back end hand
	Applicable workpiece size	Outer diameter	mm (in.)	ϕ 40−200 (ϕ1.6−7.9)
		Length	mm (in.)	20−150 (0.8−5.9)
		Max. mass	kg (lb.)	10

[ ] Option

Figure 2.3.2.2 Gantry-type loader system proposition by DMG Mori Seiki [73].

As can be seen in the figure above, for example the maximum loading capacity is 75 kg which is insufficient for most workpieces.

2.4 ORIGINAL CUTTING SEQUENCE

The original cutting sequence refers to state of the art at the beginning of this project. It can be simplified to machining different functional and non-functional element of the locking bolts previously presented.

2.4.1 Machining sequence of elements

Machining sequence represents the order in which the elements of the head bolt are machined.

It can be divided into two operations on the same machine. The workpiece is transferred between the two operations thanks to synchronised spindles.

Clamping during the first operation can be seen in the figure below.

Figure 2.4.1.1 Workpiece clamped for operation 1.

First operation is schematically represented in the following figure.

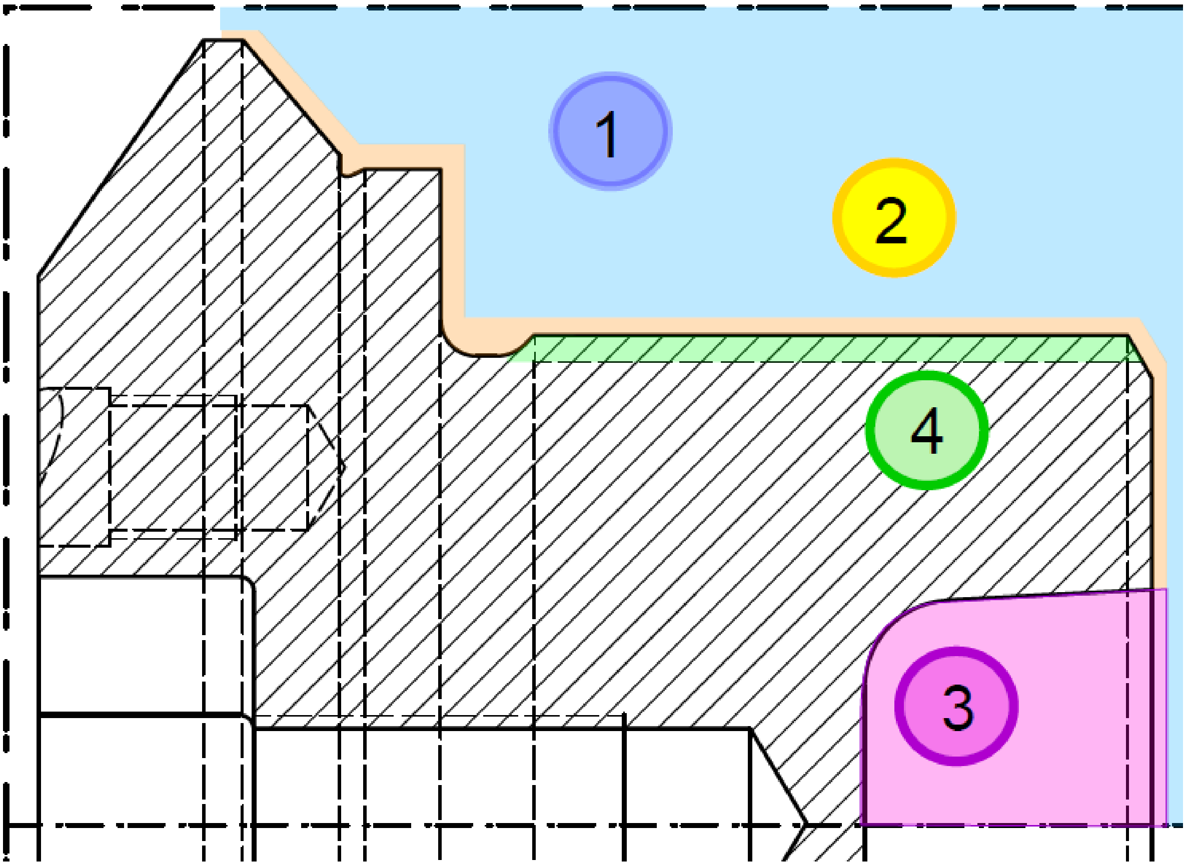


Figure 2.4.1.2 Operation 1 of locking bolt machining: 1) roughing 2) finishing and contouring 3) bottom pocket machining 4) external thread turning.

The first step of locking bolt machining was roughing and it consists of face turning and cylindrical turning.

The second step was finishing of the whole external contour consisting of 4 sub-steps (cylindrical turning with chamfer, groove contouring, face turning, contour turning).

The third step was machining of a pocket on the bottom face of the locking bolt. The pocket was machined by drilling and then boring.

The fourth machined element was external thread fabricated by thread turning.

After machining of the external thread, workpiece was transferred to the auxiliary synchronized spindle. After the transfer, operation 2 was machined.

Clamping of the workpiece during the second operation can be seen on the figure below.

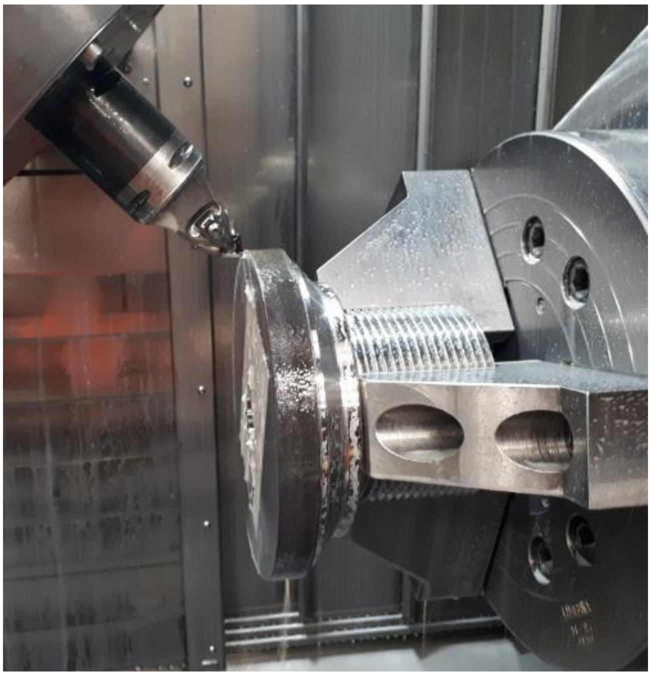


Figure 2.4.1.3 Clamping of the workpiece during the second operation (auxiliary spindle).

Second operation is displayed schematically in the following figure:

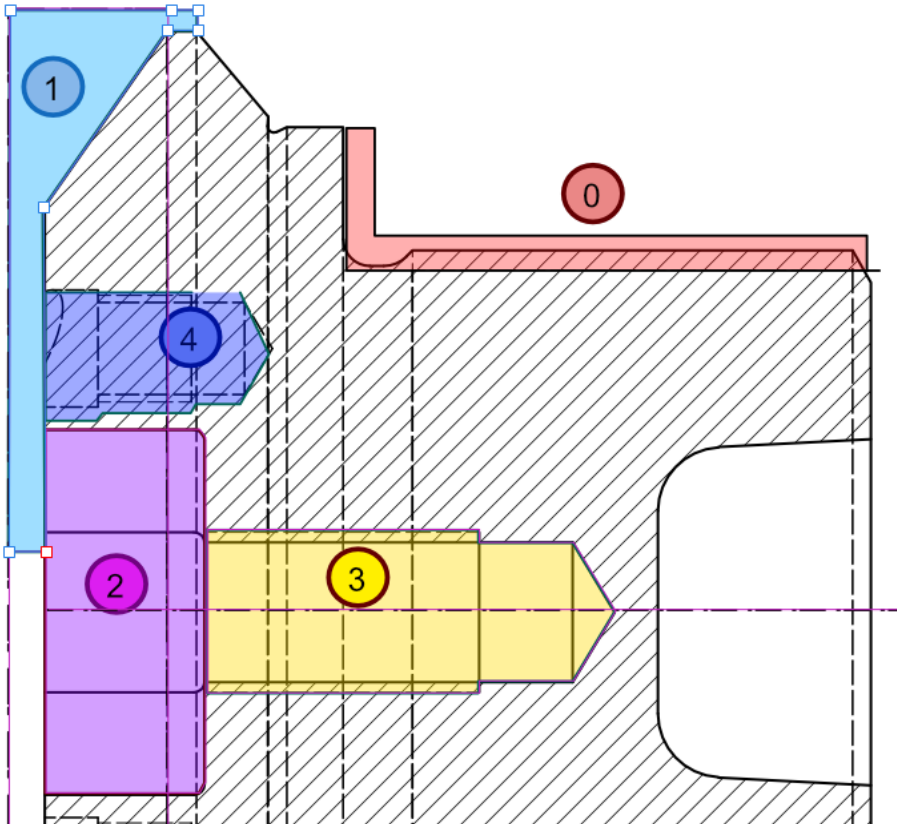


Figure 2.4.1.4 Operation 2 of locking bolt machining: 1) roughing 2) pocket machining 3) threaded central hole machining 4) small off-centre threaded holes machining.

During the second operation, the workpiece was held by the external thread previously machined during the first operation (number 0 on the figure above). Soft jaws were used not to damage or deform the machined surface of the external thread. Soft jaws are less hard than the workpiece material. The fastening pressure was lower.

The first step of the second operation was roughing.

The second step of the second operation was pocket machining. The pocket on the top surface of the locking bolt was fabricated by drilling, turning and milling.

The third step was the central threaded hole machining performed by drilling and internal thread turning,

The fourth step was machining of smaller threaded holes by drilling and thread tapping.

More detailed original cutting sequence of locking bolt HP3 with detailed steps is shown in the following figure. It was obtained by analysing the ISO code.

Table 2.4.1.1 Original cutting sequence of locking bolt HP3

N°block	step	type of machining	roughing/finishing	Tool number	N (tr/min)	vc (m/min)	f (mm)	ap (mm)
N10	(N10 drilling D.36)	drilling	roughing	T1150	884	100	0.15	
N20	(N20 roughing FACE-T01)	face turning	roughing	T1001	238	180	0.32	3
N30	(N30 roughing D.EXT.-T01)	face turning	roughing	T1001	239	180	0.32	3
N40	N40 boring, roughing and finishing)	boring	roughing and finishing	T1006	164; 182	180; 200	0.32; 0.2	3; 0.6
N50	N50 (finishing FACE)	face turning	finishing	T1006	568	250	0.2	3
N60	(N60 finishing -T66)	cylindrical turning	finishing	T1066	365	250	0.2	2
N70	(N70 GROOVE-T66)	turning	roughing and finishing	T1066	164	180	0.3	1,5 ; variable
N75	(N75 turning-T66)	turning	roughing and finishing	T1066	219	150	F.2	variable
N80	(N80 finishing FACE-T66)	face turning	finishing	T1066		250	0.2	0.4
N90	(N90 finishing , ANGLE, EXT. D-T66)	face turning and cylindrical turning	finishing	T1066	3979	250	0.2	0.41
N100	(N100 thread turning M140x6-T04)	thread turning	roughing and finishing	T1004	250	173	F6	0.23
N110	(N110 transfer to auxiliary spindland04)	X	X					
N120	(N120 drilling D.42)	drilling	roughing	T1049	884	117	0.15	
N130	(N130 turning D. EXT.-T01)	cylindrical turning	roughing	T1001	256	180	0.3	3
N140	(N140 turning D. EXT.-T01)	cylindrical turning	finishing	T1001		180	0.3	3
N150	(N150 roughing FACE-T01)	face turning	roughing	T1001		180	0.4	3
N160	(N160 pockand - boring T06)	boring	roughing and finishing	T1006		S180, S191	F.25	3
N170	(N170 pockand milling-T20 FRAISE D:25)	milling	roughing and finishing	T1020	300		F5000, F300	
N180	(N180 pockand milling-T20 FRAISE D:25)	milling	roughing	T1020	300			
N190	(N190 drilling D.22-FORand D:22.00 L:109)	drilling		T1010	868		F130.2	
N200	(N200 drilling D.17.5-FORand D:17.50 L:175.2)	drilling		T1018	868		F181.8	
N210	(N210 tapping M20-TARAUD M20.X2.5)	tapping	roughing and finishing	T1019	225		F2.5	2.5
N220	(N220 drilling D.26.5-FORand D.26.5 T7)	drilling		T1007	1200			
N230	(N230 CHANFREIN SUR EVIDEMENT-CHANFR. D:12.00 A:45)	chamfering		T1015	4000		F2400. , F5000.	
N240	(N240 CHANFREIN SUR D.22-CHANFR. D:12.00 A:45)	chamfering	roughing and finishing	T1015	4000		F2400. , F5000.	
N250	(N250 CHANFREIN SUR D.22-CHANFR. D:12.00 A:45)	chamfering	roughing and finishing	T1015	4000		F2400. , F5000.	
N260	(N260 CHANFREIN SUR D.22-CHANFR. D:12.00 A:45)	chamfering	roughing and finishing	T1015	4000		F2400. , F5000.	
N270	(N270 CHANFREIN SUR D.22-CHANFR. D:12.00 A:45)	chamfering	roughing and finishing	T1015	4000		F2400. , F5000.	
N280	(N280 CHANFREIN SUR D.26.5-CHANFR. D:12.00 A:45)	chamfering	roughing and finishing	T1015	4000		F2400. , F5000.	
N290	(N290 FILandAGE M30x3.5-T29)	internal thread turning	roughing and finishing	T1029	900		F3.5	

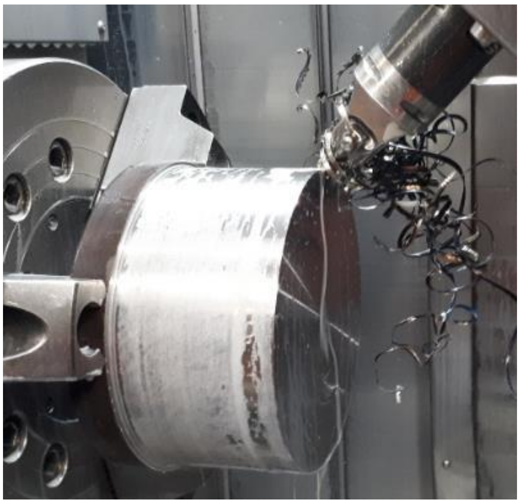
2.5 PRODUCTION OBSERVATIONS

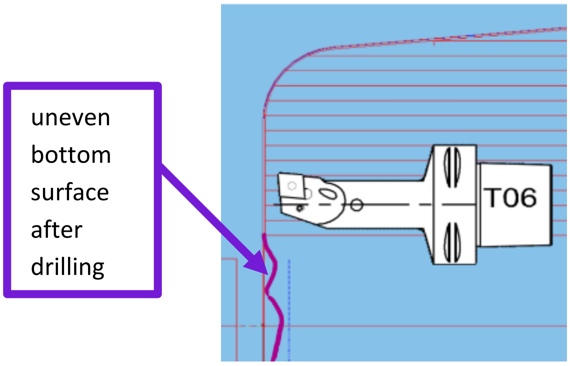
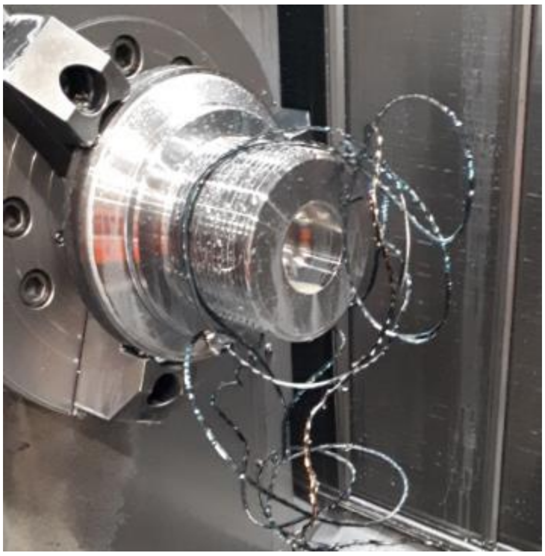
Original cutting sequence was observed in production at the beginning of the internship. Identifying problems and non-programmed machine stops was essential.

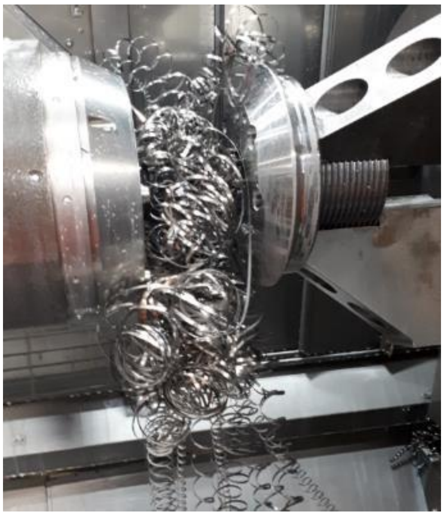
2.5.1 Identification of problems

Problems identifies during observation in production are listed in the table below.

Table 2.5.1.1 Observations of problems during machining of locking bolts.

Operation	Phase	Tool		Photo/illustration
1	External diameter roughing	T1001, Rouging insert CNMG16	long unfragmented chips	
1	Finishing + groove turning	T1066, finishing insert VNMG12	long unfragmented chips, stuck on the tool and on the workpiece	

1	boring (finishing)	T1006, insert CNMG12	predrellied hole before turning left uneven bottom surface, boring tool insert often broke during the finishing of the pocket turning	
1	external thread turning	T1004	long unfragmented chips, blocking chip conveyor, must be cut manually with pincers	
2	cylindrical turning - roughing	T1001, Rouging insert CNMG12	chip in form of a ring, need to be manually taken out	

2	boring (roughing)	T1006, insert CNMG12	unfragmented chips stuck on the tool änd workpiece	
2	thread tapping	cutting tap	unfragmented chips stuck on the tool every time	
2	internal thread turning	T1029, thread turning insert	Chips long, stuck in the threaded hole, needed to be taken out manually, facets on the thread	

2.5.1.1 Operator’s interventions

Operator intervened the most to manually eliminate chips that were stuck around the tool, workpiece or take out accumulation of unfragmented chips that would otherwise block the conveyor.

Others unprogrammed interventions were to change the cutting insert. When the cutting insert developed critical tool wear, indicator of consumed power went straight up. Consumed power going up means that the specific cutting pressure increased due to tool wear and the tool was no longer cutting sufficiently.

Operator changed manually cutting parameter of feed, especially for drilling the feeds were almost always changed for security reasons.

2.5.2 Proposed solutions

Following solutions were proposed.

Table 2.5.2.1 Solution proposed to solve problems observed in production.

Operation	Phase	Tool		Proposed solution
1	External diameter roughing	T1001, Rouging insert CNMG16	long unfragmented chips	Elaborate chip fragmentation study and try new cutting inserts for roughing
1	Finishing + groove turning	T1066, finishing insert VNMG12	long unfragmented chips, stuck on the tool and on the workpiece	Elaborate chip fragmentation study and try new cutting inserts for finishing
1	boring (finishing)	T1006, insert CNMG12	Pre-drilled hole before turning left uneven bottom surface, boring tool insert often broke during the finishing of the pocket turning	add a pass of finishing (integrate new finishing tool)
1	external thread turning	T1004	long unfragmented chips, blocking chip conveyor, must be cut manually with pincers	try different infeed methods
2	cylindrical turning - roughing	T1001, Rouging insert CNMG12	chip in form of a ring, need to be manually taken out	machine the contour in opposite sense, pushing the ring into to the left side and evacuating it
2	boring (roughing)	T1006, insert CNMG12	unfragmented chips stuck on the tool and workpiece	Elaborate chip fragmentation study and try new cutting inserts for boring
2	thread tapping	cutting tap	unfragmented chips stuck on the tool every time	replace taps with thread milling tools that produce fragmented chips
2	internal thread turning	T1029, thread turning insert	Chips long, stuck in the threaded hole, needed to be taken out manually, facets on the thread	replace thread turning with thread milling tools that produce fragmented chips

Investigation of proposed solutions led to experimentations that are presented in the third section of this thesis.

2.6 AUTOMATISATION STUDY

Automation of the machining process is an objective for the future and was not an objective of this study. This study is the first step in the direction of automating the process one day. At the beginning of this study, the machining process was not at all optimised which immediately eliminated the possibility to automate the fabrication process. In this study, automation possibilities for the machine are going to be discussed only briefly as a preliminary work for the continuation of the optimization process.

The initiative of automating the workpiece feed for head bolts has its indispensable conditions and has multiple problems.

The problems of automating the machining process:

- the machine is quite outdated (from 2003)
- automated workpiece feed is desired only for one family of parts while the machine is used to machine other types of components,
- components are fabricated in small series and the series fabricated each week vary accordingly to client demand.

Because the machine is outdated, some of critical conditions for automation are not met:

- old software interface not sufficient for communication with the robot,
- insufficient memory
- absence of automated tool setter,
- absence of workpiece touch probe,
- absence of automated door closing/opening,

To discuss the options for future automation of the machine, following companies were contacted:

- company DMG Mori to discuss the machine retrofit,
- company TechPlus to discuss robotization options.

The company TechPlus provided following checklist of necessary systems present on the machine.

The cost of the retrofit may be a setback and a question rises up if an integration of a new, more adapted machine wouldn’t be more adapted for automatised machining process rather than investment in retrofit of the old CNC machine.

3 EXPERIMENTAL STUDY

For the experimental part, propositions elaborated in the Case Study were applied to obtain information needed to resolve the problems encountered.

Goals of the experimental part were to optimize tools, machining conditions and machining strategies, in order to increase the level of autonomy of the machine. The goal measured was autonomy time while machining – work of the machine without operator's surveillance or interventions.

Unfortunately, the pandemic of 2020 greatly influenced many aspects of this project and its experimental part. For more than half of the duration of this project, only remote work was possible. Even after deconfinement, the time available at the machine was limited and the volume of production was influenced as well.

3.1 EQUIPMENT

CNC machine NT 4250 DCG Turn & Mill machine by DMG Mori that was previously presented in the case study was also used for the experimental part of this study.

Toolholders available in the workshop were used. If possible, toolholders already used in production of studied part were used to minimize investments and too many changes in CAM programs. Some new more adapted toolholders were used as well.

Aside from the CNC machine, attachments, tools and indexable inserts, additional equipment was needed.

The used additional equipment was:

- tool pre-setter Trimos Duo Display,
- Renishaw tool setting arm (equipment for the CNC machine, not integrated),
- digital microscope 1000X,
- Rugosimeter MarsSurfPS1,
- Magnifying glass LMT Belin,
- BOSH grinder,
- Hand drill with abrasive attachment,
- non-destructive tester of hardness Equotip Piccolo 2.

3.1.1 Tools and toolholders

Many of the tools used in the original cutting sequence were not used with optimal cutting conditions. Optimizing already used tools could be a favourable solution because of initial investment in new tools and toolholders can be expensive. On the other hand if the original tool didn't prove to be well adapted for the operation,

3.1.2 Tool pre-setter Trimos Optima

A tool pre-setter was used to measure the tools to be able to entre accurate tool length and/or tool diameter to the machine before putting the cutting tool into the tool magazine. Trimos Optima tool pre-setter with Trimos Duo Display was used. The display is used for operating the software and it also shows what camera of the tool pre-setter is recording. The display has a label printer integrated; therefore the label with information of the tool measurement can be put directly on the toolholder for information.

Tools were measured before being put to the tool magazine of the machine. The measurements of the pre-setter were then manually entered to the machine as tool correctors.

Trimos Optima setter in use can be seen in the following picture.

Figure 3.1.2.1 Trimos Optima tool pre-setter.

3.1.3 Renishaw HPRA tool setting arm

HPRA stands for high precision removable arm. The Renishaw HRPA tool setting arm is often used by the operators of the CNC machine that is used to machine studied components.

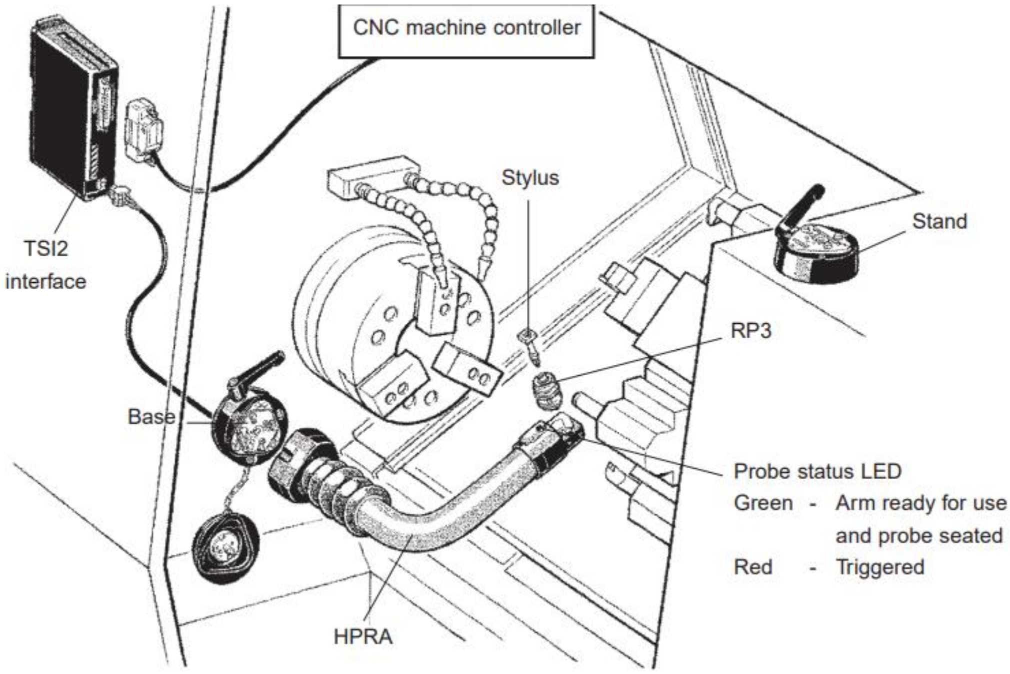


Figure 3.1.3.1 The Renishaw HRPA tool setting arm schematic drawing. [74]

The setting arm can be manually inserted to the machine to perform palping of the tool.

Tool setting armed manually attached to the interior of the NC machine ready to palp a tool is shown in the following figure.

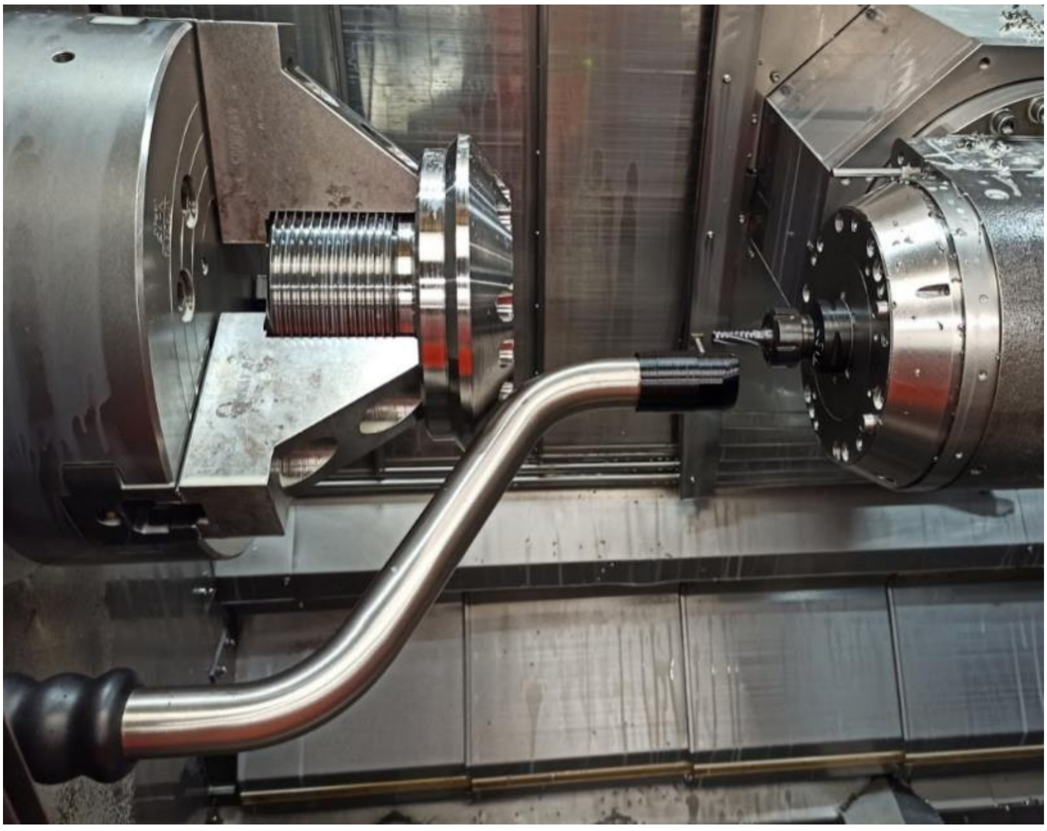


Figure 3.1.3.2 Renishaw HRPA tool setting arm in use during machining of a locking bolt.

3.1.4 Portable non-destructive metal tester of hardness

Equotip Piccolo 2 is a portable non-destructive metal testing instrument that was used for the study of material hardness.

Equotip Piccolo 2 uses the Leeb rebound method to evaluate hardness and displays the corresponding value of hardness in chosen scale (Vickers, Brinell, …). The Leeb rebound principle uses comparison of energy of the body before and after the impact with the tested metal. This energy quotient is evaluated by measuring the velocity before and after the impact with the metal. When the body rebounds from a harder material, the rebound velocity is higher The units in which the hardness is measured are HL, so called hardness of Leeb [75].

The software in the Equotip Piccolo 2 translate the measured hardness of Leeb HL to HRC, HB or HV.

Figure 3.1.4.1 Equotip Piccolo 2 portable tester of hardness [75].

Requirements for workpiece preparation are listed in the table in the figure below.

Essential Equotip Requirements

Surface preparation of the sample	
Roughness class ISO	N7
Maximum roughness depth Rt	10 µm
Centre line average Ra, CLA, AA	2 µm
Indentation on sample at 760 HLD (600 HV, 55 HRC)	
Diameter	0.45 mm
Depth	17 µm

Minimum weight of sample	
Compact sample shape	5 kg
Sample on solid support	2 kg
Sample coupled to solid support	0.1 kg
Minimum thickness of sample	
Uncoupled / Coupled	25 mm / 3 mm
Surface layer thickness	0.8 mm

Figure 3.1.4.2 Equotip sample requirements [75].

The measured surface needs to be prepared before using the device: sufficiently little roughness and degreasing are needed before.

3.2 PLANNING OF EXPERIMENTS

Planning of the experiments consisted of multiple phases:

- first conception,
- economic study,
- verification by superiors,
- time planning,
- detailed conception,
- experimentations.

Firstly, a basic conception of experiments was drafted. Secondly an economic revenue of experiments was calculated. After validation of the economic study by direction, more detailed conception of experiments and a time planning were prepared. The total days spend on experiments was determined as 6 workdays with possibility to divide them into half workdays.

Following experimentations were defined:

1) experimental study of material hardness,
2) chip fragmentation during external cylindrical roughing,
3) chip fragmentation during external cylindrical finishing,
4) chip fragmentation during boring (roughing and finishing),
5) internal thread milling,
6) external thread turning,
7) trochoidal milling,
8) additional experimentations if needed.

3.2.1 Economical study

Study of return of investment in the experiments was conducted. The economical, study of the problem served to justify investment in experimentations and how quickly the initial investment would return during normal production even without automation or robotization of workpiece feed.

Using more expensive tools like thread milling cutters needed to be justified economically.

Cost of producing a machined element was calculated following the equation below [22]:

$$C_{production} = M \cdot t_m + M \cdot t_l + M \frac{t_m}{T} \cdot t_c + \frac{t_m}{T} C_t \quad (11)$$

Where:

- $C_{production}$ … production cost,
- t_m … total machining cost per unit of time (both pay of operator and machine cost),
- t_c … tool changing time,
- T … tool life,
- C_t … tool cost,
- M … operator's wage plus machine cost per unit of time,
- t_l … non-productive time.

Table 3.2.1.1 Economic study for small threaded holes for locking bolt HP3.

tapping								
Step	Price of machining	Price of machine 1/min	Temps machining without cutting	Temps machining (min)	Price of 1 arête de coup	Tool life outil	Tool change time	Price (€)
drilling	0.41	1.73	0.00	0.20	5.00	20.00	1.00	1.85
tapping	1.44	1.73	0.00	0.12	122.00	11.67	1.00	

thread milling								
Step	Price of machining	Price of machine 1/min	Temps machining without cutting	Temps machining (min)	Price of 1 arête de coup	Tool life outil	Tool change time	Price (€)
drilling	0.41	1.73	0.00	0.20	5.00	20.00	1.00	1.20
milling cutter M20	0.78	1.73	0.05	0.17	329.00	180.00	5.00	

N of elements	case	price/instance	gained/part
4	tapping - original	1.854	- €
4	filetage	1.195	2.63 €

Table 3.2.1.2 Economic study for central internal thread M30x3.5 for locking bolt HP3.

turning internal thread								
Step	Price of machining	Price of machine 1/min	Temps machining without cutting (min)	Temps machining (min)	Price of 1 arête de coup	Tool life outil	Tool change time	Total price (€)
drilling	1.00	1.73	0.00	0.50	5.00	25.00	1.00	2.80
turning M30	1.79	1.73	0.20	0.60	8.87	20.80	1.00	

Milling tool for M30										
Step	Price of machining	Price of machine 1/min	Temps machining without cutting (min)	Temps machining (min)	Price of 1 arête de coup	Tool life outil	Tool change time	Note	Note2	Total price (€)
drilling	1.20	1.73	0.00	0.60	5.00	25.00	1.00	0.00	0.00	2.18
thread milling cutter with inserts Walter	0.97	1.73		0.55	4.00	150.00	1.00		chips forcement	

HP3			
n of elements	case	price/instance	gained/ part
1	turning (original)	2.796	- €
1	thread milling M30 (new strategy)	2.176	0.62 €

Table 3.2.1.3 Economic study for pocket milling for locking bolt HP3.

case 1 : turning+milling - old strategy								
Step	Price of machining (€)	Price of machine €/min	Temps machining without cutting (min)	Temps machining (min)	Price of 1 cutting edge (€)	Tool life (min)	Tool change time (min)	Price oper machined elemnt (slot)
boring - old	4.41	1.73	0.50	1.20	7.80	10.00	0.50	9.78
slot milling - old strategy	5.37	1.73	1.50	1.00	19.78	55.80	2.00	

case 2: turning+milling - new strategy								
Step	Price of machining	Price of machine 1/min	Temps machining without cutting	Temps machining (min)	Price of 1 arête de coup	Tool life outil	Tool change time	Price of par instance (slot
boring	3.35	1.73	0.30	1.20	7.80	19.00	1.00	4.65
milling slot - new strategy	1.30	1.73	0.09	0.33	135.00	100.00	1.00	

n of elements	case	price/instance	gained/part
2	Original	9.78	- €
2	Trochoïdale + turning	4.65	10.26 €

As can be seen in the tables above, estimation of production cost of certain machined elements was favorable to testing ang possibly implementing the new strategies and new tools.

3.3 EXPERIMENT 1: EXPERIMENTAL STUDY OF THE MATERIAL HARDNESS

Hardness of workpieces was investigated multiple times during the observation stage of the project. Unfortunately, because of events in 2020, for a few months only remote work was possible and further studies of hardness took place only later, in June and July 2020.

More detailed study of hardness was conducted on workpieces intended for machining experiments because hardness influences machinability and it was important to know the hardness for reference. For hardness comparison two representative types of workpieces were chosen. Each type of workpieces represented either the workpieces of smaller dimensions or the workpieces with larger dimensions.

Evolution of hardness in function of distance from centre of the workpiece was investigated.

The measurement of hardness was conducted with a portable device, which is not very accurate but allows comparing values that had been taken with the same device.

The measured values are of comparative nature between each other, for example to observe variations between different diameters of workpieces.

3.3.1 Workpieces for material hardness measurements

Occasionally, the workpieces were measured for hardness in production during observation stage of this study. On the other hand, the process of preparation of the surface takes too much time to be a part of every small series of workpieces.

For more detailed study of hardness, four series of workpieces were chosen:

- two series of workpieces HP3 – first of 6 workpieces, second of 4 workpieces,
- one series of 3 workpieces HP5,
- one series of 2 workpieces HP6.

The lots chosen were the one used later for machining testing. This allowed not only a study of material hardness but also to determine the hardness of workpieces for their machining experimentations.

3.3.2 Surface preparation

As was described in the portion describing the Equotip Piccolo 2, before testing the material hardness with this device, the surface needs to be prepared to obtain sufficiently little roughness. To obtain sufficient roughness, two step grinding was performed. The surface also needs to be degreased.

The process of surface preparation before the measurements of hardness is illustrated in the table below.

Table 3.3.2.1 Steps of surface preparation of workpieces for hardness measurements.

Step	Illustrative photos
Workpieces before any surface preparations	
Bosch grinder used for first surface grinding	

Workpieces after first grinding	
Hand drill with grinding attachment used for secondary grinding	

Secondary grinding of workpieces	
Degreasing spray used: Wurth W-Power	

Workpieces with surfaces fully prepared for hardness measurement	

3.3.3 Measurements

After surface preparations, the workpieces were ready to be evaluated in hardness.

Firstly, distances from the workpiece surface were marked to create zones to measure the hardness. Then the measuring device was set to measure the hardness according to Brinell (HB).

The workpieces were divided into small zones. Three measurements per zone were then taken to obtain average value per zone.

It must me noted that portable measurement of hardness does not give precise value of hardness. Nevertheless, the measurements can be used to compare the workpieces between each other and give an approximative value of hardness.

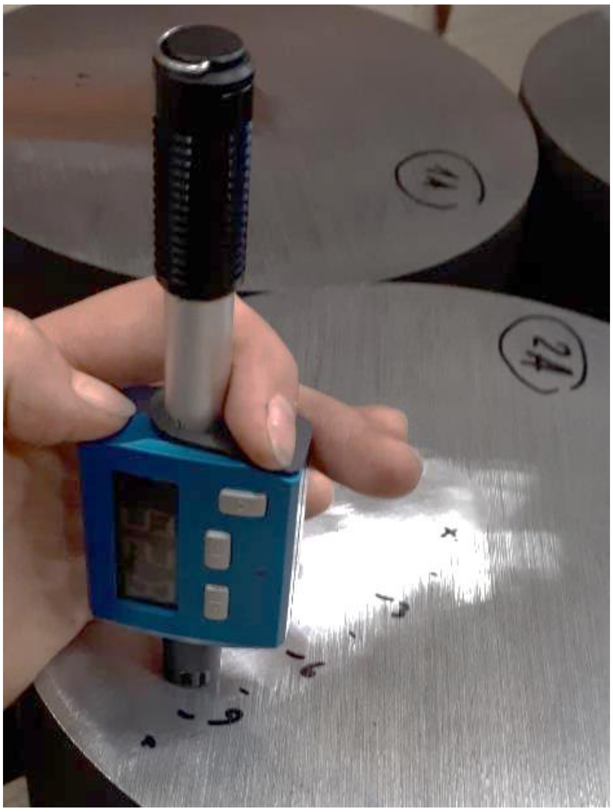
Table 3.3.3.1 Steps during measurements of hardness

Step	Illustration photo
Workpieces with prepared surfaces for hardness test	

Branding the workpieces	
Marking zones for measurement on the workpiece surface	

Portable non-destructive metal tester of hardness Equotip Piccolo presetting to HB values

Device placement before measurement	

Device placement during measurement, with value of hardness displayed (in HB)	
Small marks left on the surface of the workpiece after measurement of hardness	

3.3.4 Material hardness measurement results

The measurements were taken in zones of distanced variably in radius from the centre.

Average value for each zone was calculated. Average value of the workpiece value was calculated for every workpiece.

The values of average value in function of the distance from the centre were plotted with linear regression. The coefficient of regression R^2 indicated how accurate the linear approximation is. The closer the value of R^2 is to value 1, the better the fit of the approximation.

Linear regressions were approximated as the closes fit. In the linear regression y corresponds to material hardness (HB) and x corresponds to distance from the centre of the workpiece in millimetres.

3.3.4.1 First series of 6 workpieces HP3

The measurements were taken in zones of 15mm in radius from the centre.

Results of this lot are displayed in the following table.

Table 3.3.4.1 Hardness of Brinell measured on different zones on the first series of 6 workpieces HP3.

6 workpieces HP3, diameter 230 mm, 16/06/2020										
distance from centre in radius (mm)	N° zone	1	2	3	4	5	6	7	8	average hardness of the workpiece
	MIN (mm)	0	15	30	45	60	75	90	105	
	MAX (mm)	15	30	45	60	75	90	105	115	
	average	7.5	22.5	37.5	52.5	67.5	82.5	97.5	110	
workpiece N°1A	value 1	224	237	225	249	246	258	274	284	222.9
	value 2	229	245	250	241	250	258	261	277	
	value 3	242	228	230	241	245	257	287	279	
	average	231.7	236.7	235.0	243.7	247.0	257.7	274.0	280.0	
workpiece N°2A	value 1	228	232	245	241	245	245	278	272	250.1
	value 2	237	222	234	247	250	261	281	273	
	value 3	235	230	243	247	248	259	271	278	
	average	233.3	228.0	240.7	245.0	247.7	255.0	276.7	274.3	
workpiece N°3A	value 1	229	239	225	230	246	245	278	280	244.8
	value 2	224	234	223	223	241	251	272	272	
	value 3	228	234	226	231	249	249	274	272	
	average	227.0	235.7	224.7	228.0	245.3	248.3	274.7	274.7	
workpiece N°4A	value 1	230	230	238	250	248	236	272	273	246.1
	value 2	228	232	229	248	244	237	256	277	
	value 3	222	229	229	245	247	255	276	275	
	average	226.7	230.3	232.0	247.7	246.3	242.7	268.0	275.0	
workpiece N°5A	value 1	229	236	252	233	247	245	270	267	248.3
	value 2	239	228	242	238	258	251	274	263	
	value 3	233	221	243	245	248	267	265	266	
	average	233.7	228.3	245.7	238.7	251.0	254.3	269.7	265.3	
workpiece N°6A	value 1	239	234	233	236	241	258	279	279	250.3
	value 2	236	232	234	231	254	263	275	282	
	value 3	231	234	235	245	242	259	274	280	
	average	235.3	233.3	234.0	237.3	245.7	260.0	276.0	280.3	

The results above are interpreted in the figure below.

Figure 3.3.4.1 Average hardness in cross section of the workpiece for first lot of 6 workpieces HP3.

3.3.4.2 **Second series of 6 workpieces HP3**

Results of this series are displayed in the following table.

Table 3.3.4.2 Hardness of Brinell measured on different zones on 6 workpieces HP3.

6 workpieces HP3, diameter 230 mm, 24/06/2020										
distance from center in radius (mm)	N°zone	1	2	3	4	5	6	7	8	average hardness of the workpiece (HB)
	MIN (mm)	0	15	30	45	60	75	90	105	
	MAX (mm)	15	30	45	60	75	90	105	115	
	average	7.5	22.5	37.5	52.5	67.5	82.5	97.5	110	
workpiece N°1B	value 1	227	234	241	241	236	257	262	272	241.2
	value 2	240	232	239	244	247	252	263	274	
	value 3	235	230	240	245	243	259	268	279	
	average	234.0	232.0	240.0	243.3	242.0	256.0	264.3	275.0	
workpiece N°2B	value 1	221	235	243	240	250	235	262	273	236.8
	value 2	222	230	239	246	244	236	252	267	
	value 3	225	224	237	245	246	245	253	270	
	average	222.7	229.7	239.7	243.7	246.7	238.7	255.7	270.0	
workpiece N°3B	value 1	270	268	284	265	269	247	291	277	267.4
	value 2	272	269	262	264	268	271	273	283	
	value 3	260	264	262	268	273	278	270	274	
	average	267.3	267.0	269.3	265.7	270.0	265.3	278.0	278.0	
workpiece N°4B	value 1	275	270	268	276	276	289	286	281	271.5
	value 2	264	283	260	262	274	277	283	280	
	value 3	262	265	266	268	282	270	282	280	
	average	267.0	272.7	264.7	268.7	277.3	278.7	283.7	280.3	
workpiece N°5B	value 1	267	261	267	265	270	283	279	281	271.8
	value 2	279	273	272	267	271	286	282	286	
	value 3	269	278	267	272	265	281	277	280	
	average	271.7	270.7	268.7	268.0	268.7	283.3	279.3	282.3	
workpiece N°6B	value 1	270	273	280	268	270	275	281	284	272.8
	value 2	268	267	269	277	278	281	282	284	
	value 3	269	272	275	274	274	271	278	287	
	average	269.0	270.7	274.7	273.0	274.0	275.7	280.3	285.0	

The results above are interpreted in the figure below.

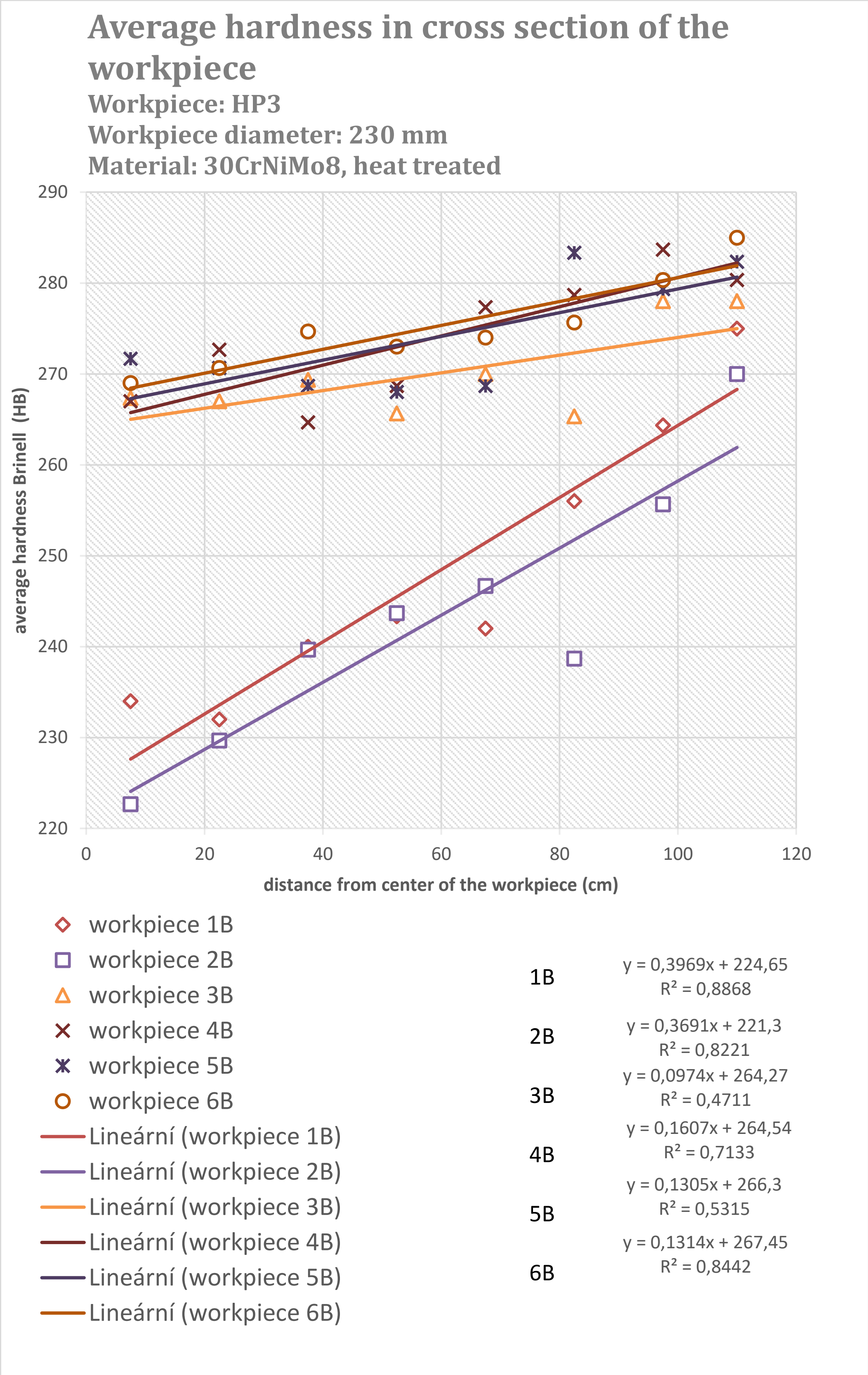


Figure 3.3.4.2 Average hardness in cross section of the workpiece for second lot of 6 workpieces HP3.

3.3.4.3 Series of 3 workpieces HP5

The measurements were taken in zones of 15mm in radius from the centre.

Results of this lot are displayed in the following table.

Table 3.3.4.3 Hardness of Brinell measured on different zones on 3 workpieces HP5.

3 workpieces HP5, diameter 230 mm, 09/06/2020								
distance from centre in radius (mm)	N° zone	1	2	3	4	5	6	average hardness of
	MIN	0	5	15	35	65	95	
	MAX	5	15	30	65	95	125	
	averag	2.5	10	22.5	50	80	110	
workpiece N°1B	value 1	298	297	295	304	326	326	307.5
	value 2	310	292	307	307	325	325	
	value 3	293	302	301	303	312	312	
	averag	300.3	297	301	304.7	321	321	
workpiece N°2B	value 1	296	283	293	297	308	333	300.6
	value 2	293	288	299	290	302	329	
	value 3	293	297	282	299	310	319	
	averag	294	289.3	291.3	295.3	306.7	327	
workpiece N°3B	value 1	294	294	285	296	295	315	267.4
	value 2	312	312	301	283	291	304	
	value 3	296	296	300	297	297	317	
	averag	300.7	300.7	295.3	292	294.3	312	

The results above are interpreted in the figure below.

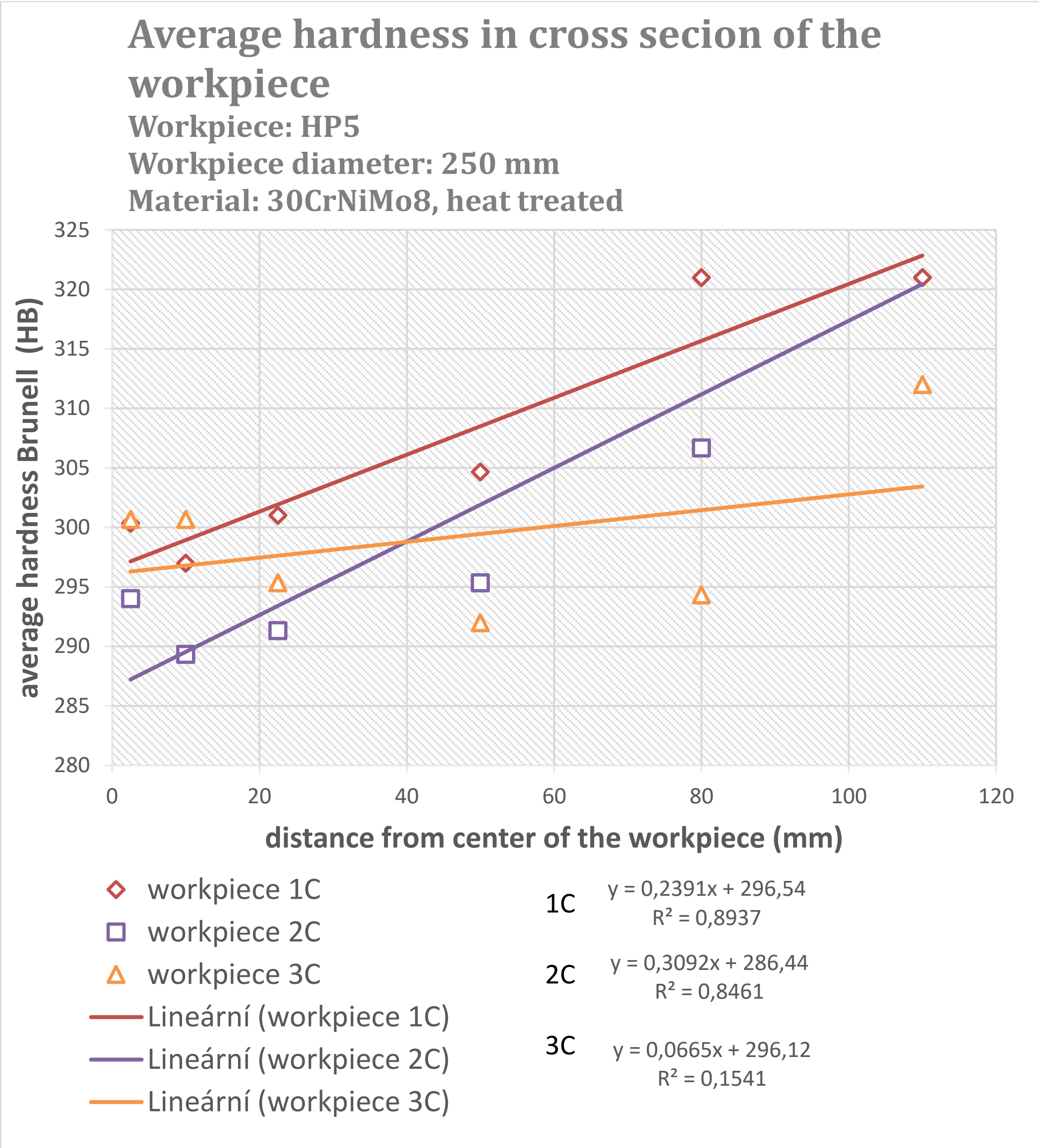


Figure 3.3.4.3 Average hardness in cross section of the workpiece for series of 3 workpieces HP5.

3.3.4.4 **Series of 2 workpieces HP6**

Results of this series are displayed in the following table.

Table 3.3.4.4 Hardness of Brinell measured on different zones on 2 workpieces HP6.

2 workpieces HP6, diameter 320 mm, 09/07/2020													
distance from center in radius (mm)	N°zone	1	2	3	4	5	6	7	8	9	10	11	average hardness of the workpiece (HB)
	MIN (mm)	0	15	30	45	60	75	90	105	120	135	150	
	MAX (mm)	15	30	45	60	75	90	105	120	135	150	161	
	average	7.5	22.5	37.5	52.5	67.5	82.5	97.5	112.5	127.5	142.5	155.5	
workpiece HP6 N°1D	value 1	271	268	271	269	262	275	266	271	294	289	297	276.6
	value 2	265	272	270	272	274	271	271	272	282	291	295	
	value 3	267	268	273	267	274	278	272	279	281	299	303	
	averag	267.7	269.3	271.3	269.3	270.0	274.7	269.7	274.0	285.7	293.0	298.3	
workpiece HP6 N°2D	value 1	270	285	285	279	270	278	287	280	288	301	293	284.7
	value 2	277	277	283	275	284	279	278	289	294	298	307	
	value 3	281	281	274	280	284	287	287	280	292	294	298	
	averag	276.0	281.0	280.7	278.0	279.3	281.3	284.0	283.0	291.3	297.7	299.3	

The results above are interpreted in the figure below.

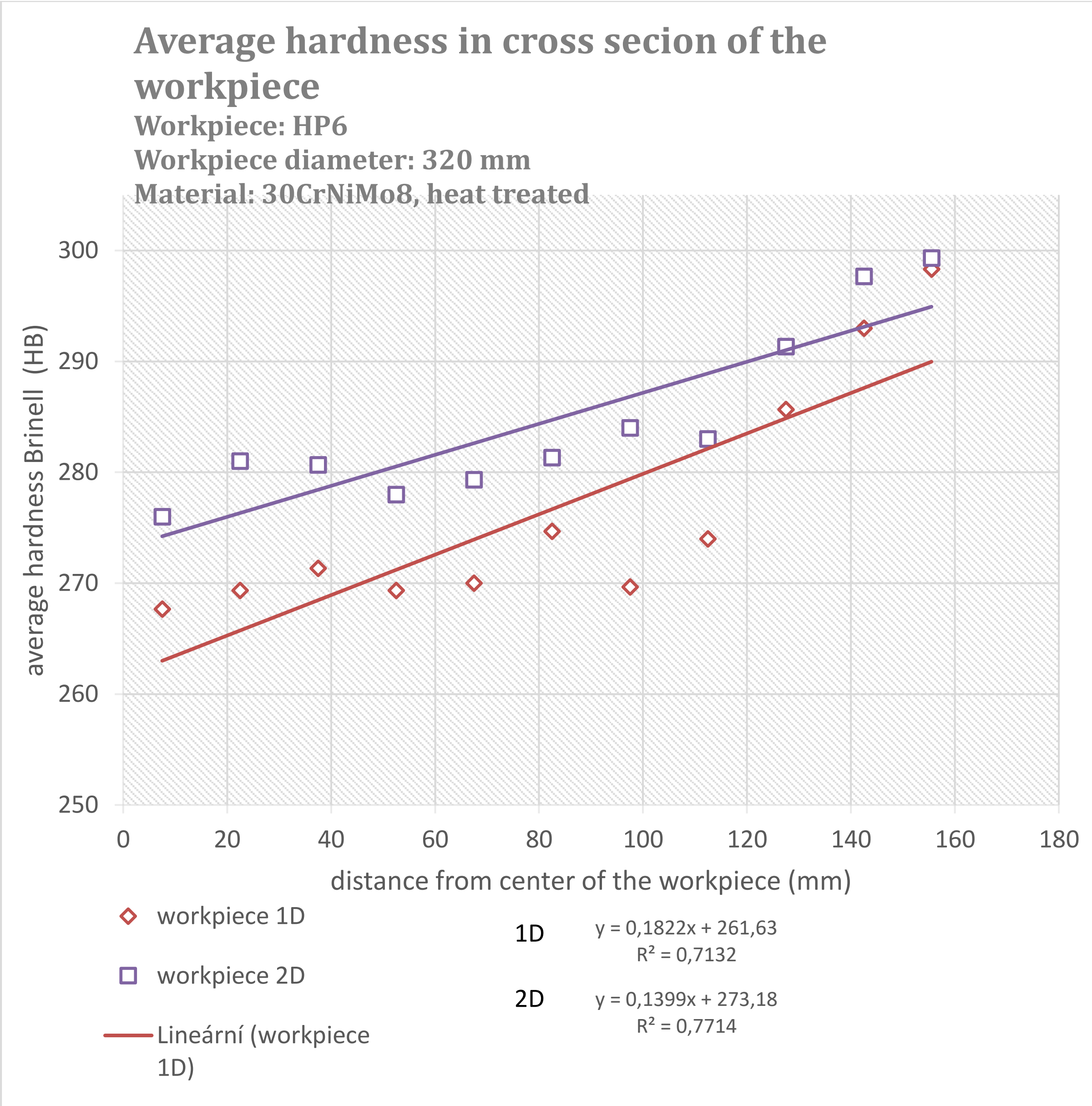


Figure 3.3.4.4 Average hardness in cross section of the workpiece for lot of 2 workpieces HP6.

3.3.5 Conclusions for the material hardness

Hardness of workpieces from 30CrNiMo8+QT material varies and stays between the limits of tensile strength guaranteed by the norm NF EN ISO 683-2.

The limits of tensile strength by this norm are 930-1130 MPa which can be converted to approximate harness of Brinell 271 to 327 HB (Hardness of Brinell) considering using 10mm steel ball and 3000kg worth of penetration force [9].

The hardness was measured with Equotip Piccolo 2 which measured the hardness of Leeb. The device itself translates the values in HL to hardness of Brinell HB, the settings of the device were set to HB as it is the preferred scale of hardness in the workshop. It should be noted that translation between the scale of hardness is empiric using translation tables and the values are not the exact equivalents.

The study of hardness of the chosen workpieces shows that the supplier delivered conforming material that respected the norm.

The workpiece material is conforming but varies in hardness which can have an influence on machinability. For next experimentations, the highest hardness of material was considered when choosing the tools and cutting parameters as a hypothesis that higher hardness in this range of values results in worse machinability.

In all studied workpieces the hardness was lower towards the centre of the workpiece. The tendencies of elevation of hardness in extremities of the workpiece can be seen in the figure below.

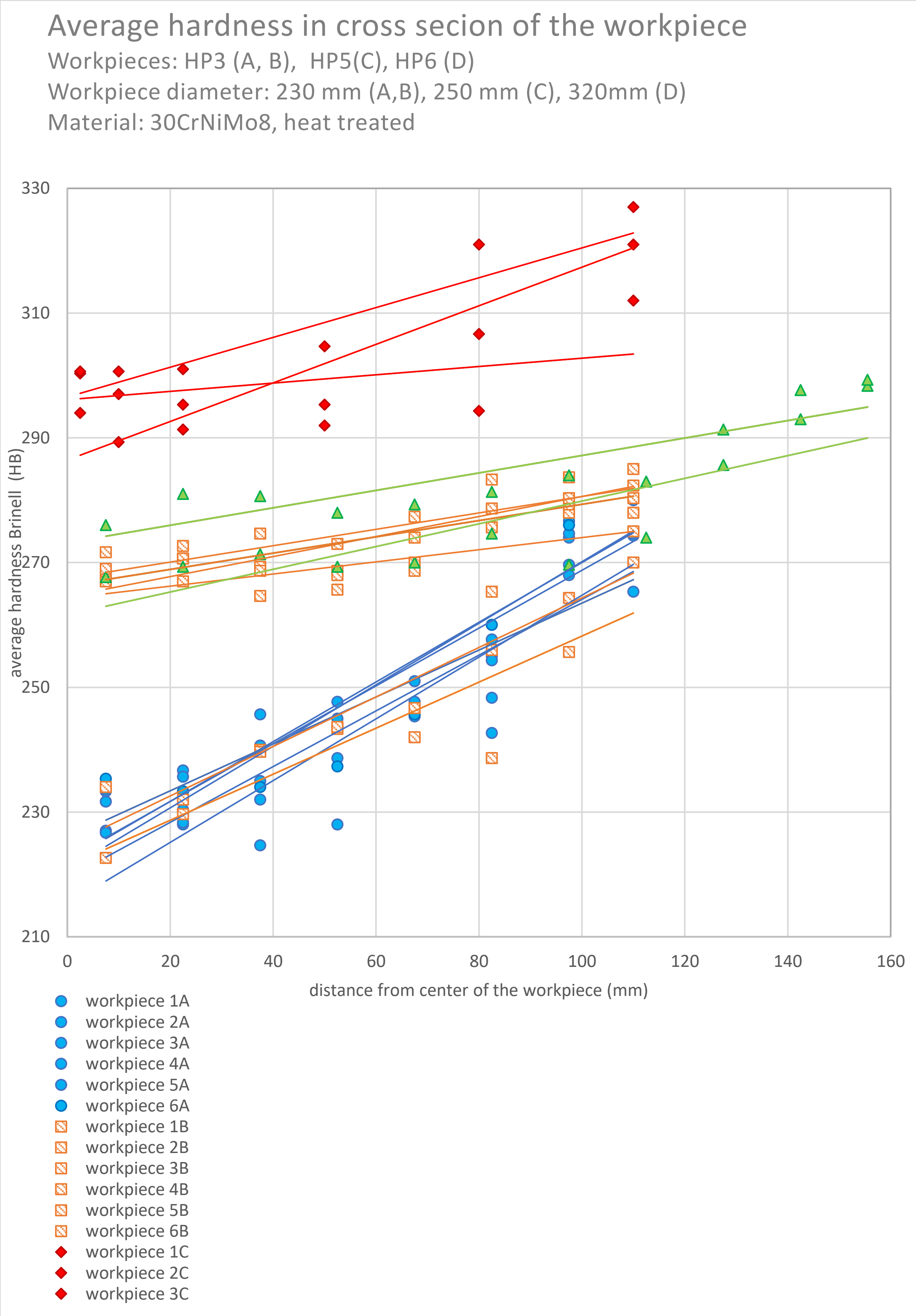


Figure 3.3.5.1 Evolution of hardness in cross section of workpieces in function of distance from the centre.

Even though a linear evolution is not an exact fit for the tendency of evolution of hardness in workpiece cross-section, the general tendency of hardness is:

- the closer to the extremity of the workpiece, the higher the hardness as it was expected due to quenching of the material,
- the highest hardness is at the zone the closest to the outer diameter.

To establish an equation that would approximate the general tendency of hardness, more data would be needed. Even with more data, an equation that would fit all workpieces probably would not exist. For the industrial context it was not necessary to establish such an equation.

The result important for the industrial context is that the workpiece hardness is quite variable. To simplify in the rest of the highest tensile strength of the material admissible by the norm translated to equivalent hardness of 361 HB was taken as a default value.

3.4 EXPERIMENT 2: CHIP FRAGMENTATION DURING ROUGHING AND SEMI-FINISHING WITH GEOMETRY CNMG

Good chip fragmentation was a critical condition for enabling the possibility to automate the machining process in the future.

To find zones of cutting parameters with good chip fragmentation,

3.4.1 Tool and inserts

Tool used was already in use in production, only tool inserts were modified.

Tool used: C6-DCLNL-45065-16.

Tool attachment used: C6-391.01-63 100A (Capto C6 attachment).

Insert geometry: CNMG 16 06 16.

General geometry of the rouging insert was kept the same as previously used, insert with different chip breakers of different manufacturers were tested.

Figure 3.4.1.1 Toolholder C6-DCLNL-45065-16.

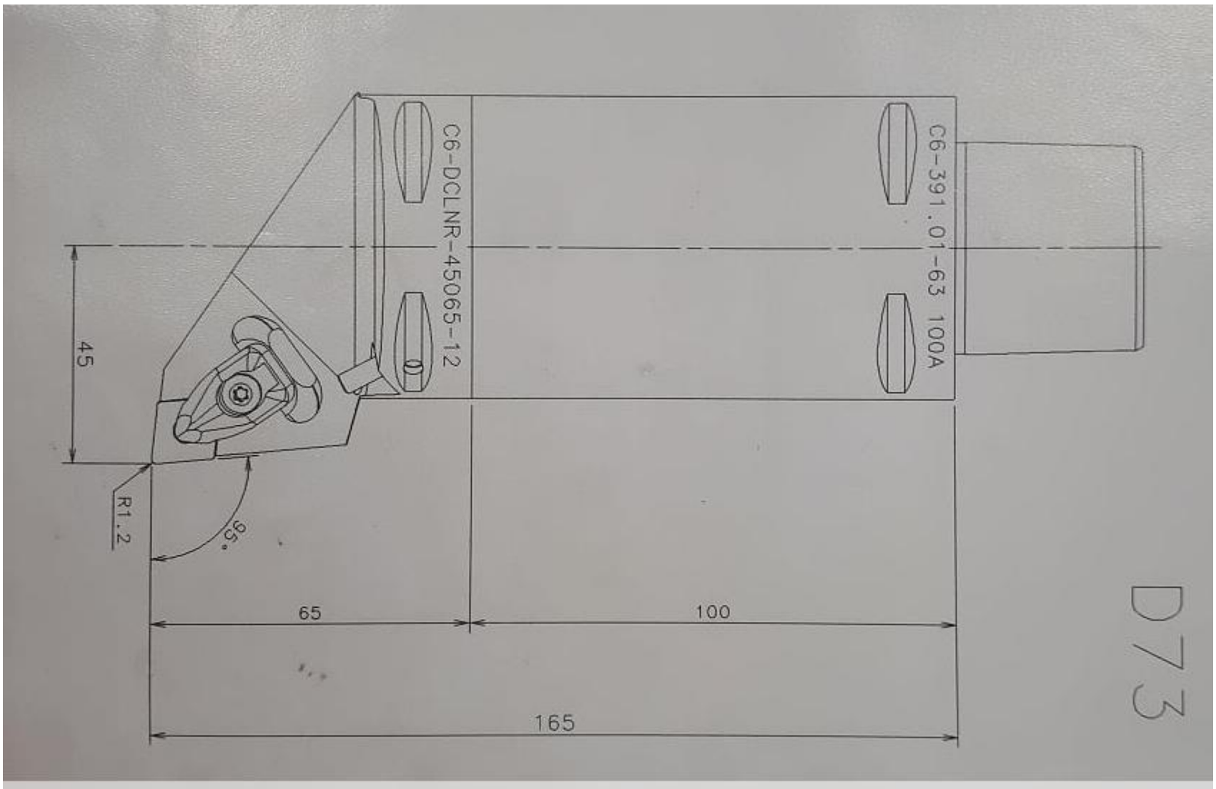


Figure 3.4.1.2 Toolholder C6-DCLNL-45065-16 with attachment C6-391.01-63 100A.

Figure 3.4.1.3 Roughing tool pre-setting using Trimos Optima tool pre-setter.

Indexable cutting inserts are listed in the table below, pictures showing different chip breaker geometries can be observed.

Table 3.4.1.1 Cutting inserts used for experimentation of roughing.

Cutting inserts CNMG 16 06 16 used for experimentation of roughing			
producer	designation	application	picture
Walter	CNMG 16 06 16-RP5 WPP10S	roughing	
Sandvik	CNMG 16 06 16 PR 4325	roughing	
Sandvik	CNMG 16 06 16 MR 4325	roughing	
Garant	CNMG 16 06 16 - SM HB7020	semi-finishing	

Indexable cutting insert used for the experimentation of chip fragmentation during roughing are listed in the table below with their admissible cutting parameters.

Table 3.4.1.2 Cutting insert with cutting parameters recommendations and cutting conditions used during the experiments of roughing.

General information			Application limits				Principle application		Recommended by producer			Values during experimentations							
producer	designation	Product information	a_p min (mm)	a_p max (mm)	f min (mm)	f max (mm)	v_c min (m/min)	v_c max (m/min)	a_p (mm)	f (mm)	v_c (m/min)	a_p 1 (mm)	a_p 2 (mm)	a_p 3 (mm)	f1 (mm)	f2 (mm)	f3 (mm)	f4 (mm)	v_c (m/min)
Walter	CNMG 16 06 16-RP5 WPP10S	producer	1.6	8	0.4	0.7	x	x	5	0.52	110	3.50	4.00	4.50	0.40	0.45	0.50	0.55	130
Sandvik	CNMG 16 06 16 PR 4325	producer	1.5	8	0.3	0.8	265	430	4.62	0.5	150	3.50	4.00	4.50	0.35	0.40	0.45	0.50	130
Sandvik	CNMG 16 06 16 MR 4325	producer	0.3	8	0.2	0.7	240	405	3.75	0.45	136	3.50	4.00	4.50	0.40	0.45	0.50	0.55	130
Garant	CNMG 16 06 16 - SM HB7020	producer	0.5	8	0.2	0.5	120	440	x	x	x	3.00	3.50	4.00	0.30	0.35	0.40	0.45	130

It can be noted that the cutting speeds recommended by producers for the used machined material are lower than for general application of the cutting inserts.

3.4.2 Preliminary computation of maximum consumed power

To ensure that during the experimentation of roughing maximum admissible power was not exceeded, value of consumed power was preliminary calculated.

For computation of the consumed power, relation presented in the theoretical analysis was used to estimate the cutting power [19] .

$$P_c = \frac{A_D \cdot v_c \cdot k_c}{60 \cdot 10^3} \cdot \frac{v_c \cdot f \cdot a_p \cdot k_c}{60\ 000} \qquad (12)$$

Maximum admissible power was 18.5 kW. The used machine's power can be 22 kW but not for longer than 30 minutes. Because roughing operations for larger locking bolts take longer than 30 minutes, the lower admissible power was used.

Verification of cutting power is in the table below.

Table 3.4.2.1 Estimation of acceptable cutting conditions.

Ref. N°	d workpiece(mm)	Vc (m/min)	Kc (MPa)	Fc (N)	f (mm)	Kr (°)	h (mm)	ap (mm)	C (Nm)	N (tr/min)	Pc (kW)
1	250	130	3400	4287.5	0.35	95	0.349	3.5	535.9375	166	9.29
2	250	130	3500	4900	0.4	95	0.398	3.5	612.5	166	10.62
3	250	130	3500	5512.5	0.45	95	0.448	3.5	689.0625	166	11.94
4	250	130	3500	6125	0.5	95	0.498	3.5	765.625	166	13.27
5	250	130	3500	6737.5	0.55	95	0.548	3.5	842.1875	166	14.60
6	250	130	3500	5512.5	0.35	95	0.349	4.5	689.0625	166	11.94
7	250	130	3500	6300	0.4	95	0.398	4.5	787.5	166	13.65
8	250	130	3500	7087.5	0.45	95	0.448	4.5	885.9375	166	15.36
9	250	130	3500	7875	0.5	95	0.498	4.5	984.375	166	17.06
10	250	130	3500	8662.5	0.55	95	0.548	4.5	1082.813	166	18.77
11	250	130	3500	6125	0.35	95	0.349	5	765.625	166	13.27
12	250	130	3500	7000	0.4	95	0.398	5	875	166	15.17
13	250	130	3500	7875	0.45	95	0.448	5	984.375	166	17.06
14	250	130	3500	8750	0.5	95	0.498	5	1093.75	166	18.96
15	250	130	3500	9625	0.55	95	0.548	5	1203.125	166	20.85

From the calculation it was clear that depth of cut 5 mm was too much for the machine, therefore the maximum tried depth of cut was determined as $a_{p,max}$ = 4.5 mm.

3.4.3 Experimentations

Before experimentations, the following procedure was followed:

- hardness of the workpiece was tested,
- the workpiece was mounted in the machine
- the oxidized surface layer was machined with the original cutting tool and insert to not influence the experimentations.

Workpiece of hardness was measured as presented in the previous chapter concerning experimental study of workpiece hardness.

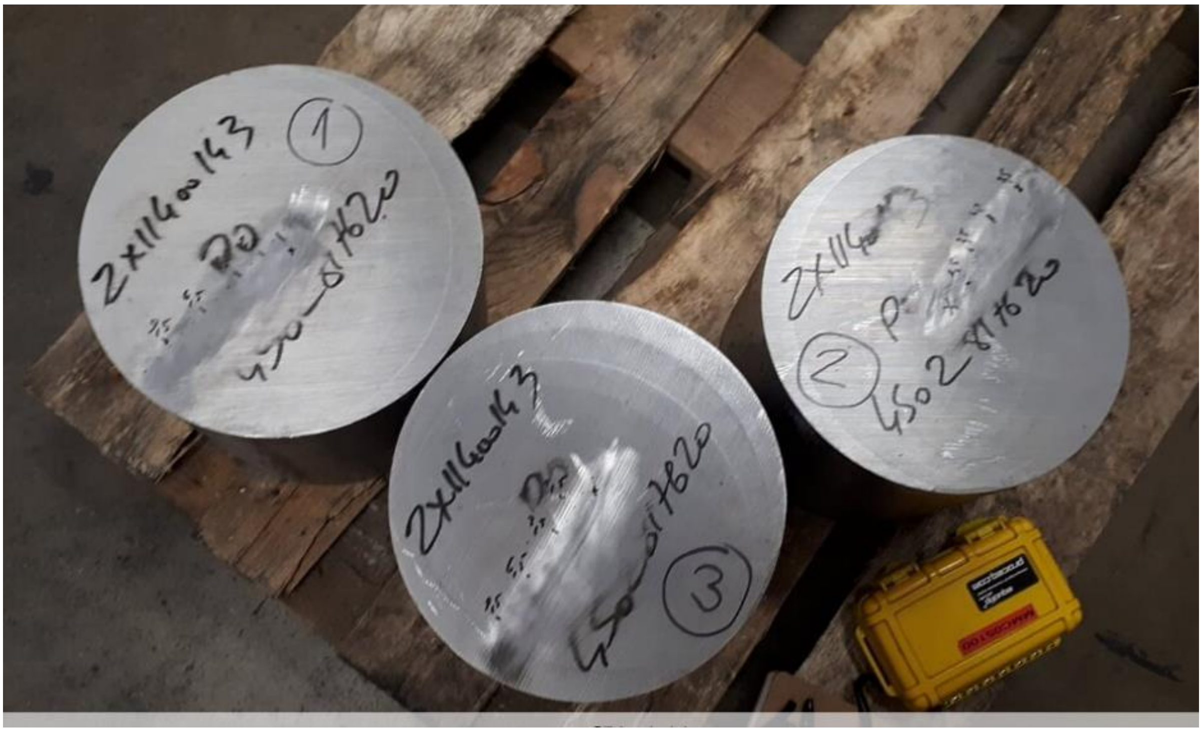


Figure 3.4.3.1 Workpieces HP5, amongst them workpiece 2C.

The CAM program in Esprit can be seen in the following figure with 4 zones distinguished.

For every group of 4 zones a depth of cut was fixed. Firstly the zone 1 was machined using feed f1. Then the tool returned to the original position and the machine was stopped to take

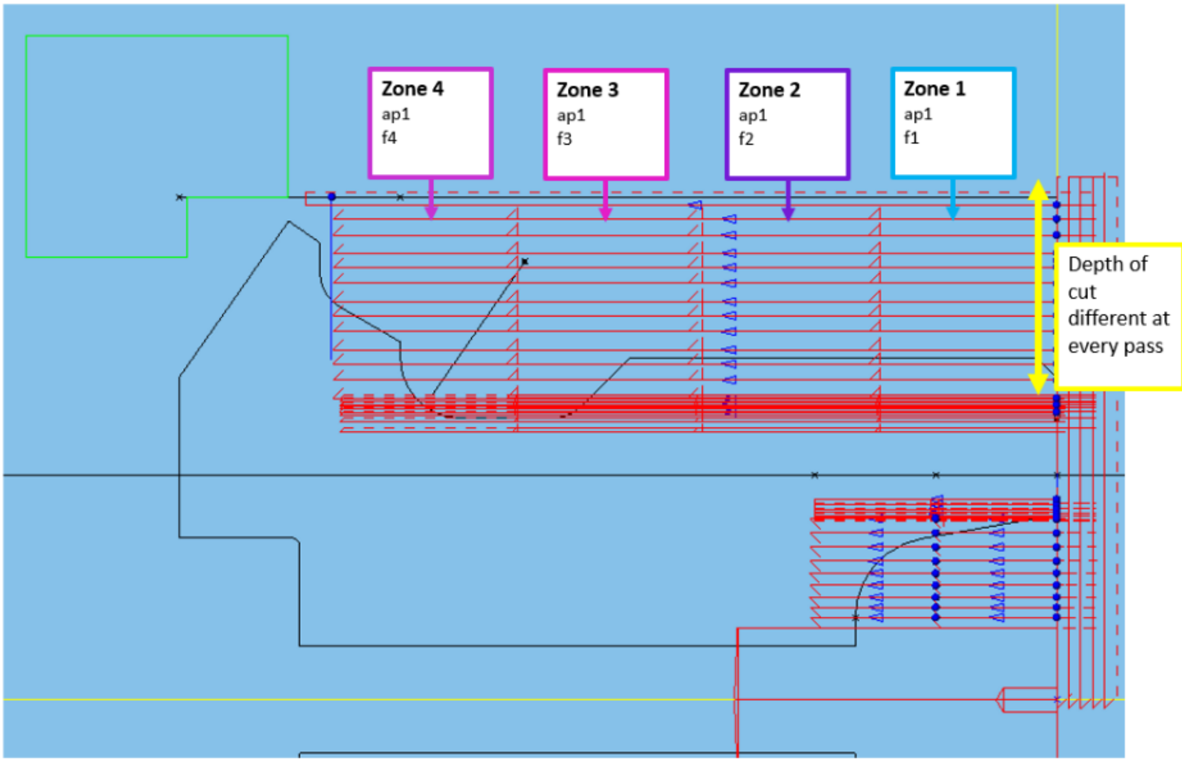


Figure 3.4.3.2 Different zones with different cutting parameters during experimentation of roughing of a locking bolt.

Because of the diameter to length ration of the workpiece, a counter spindle was used.

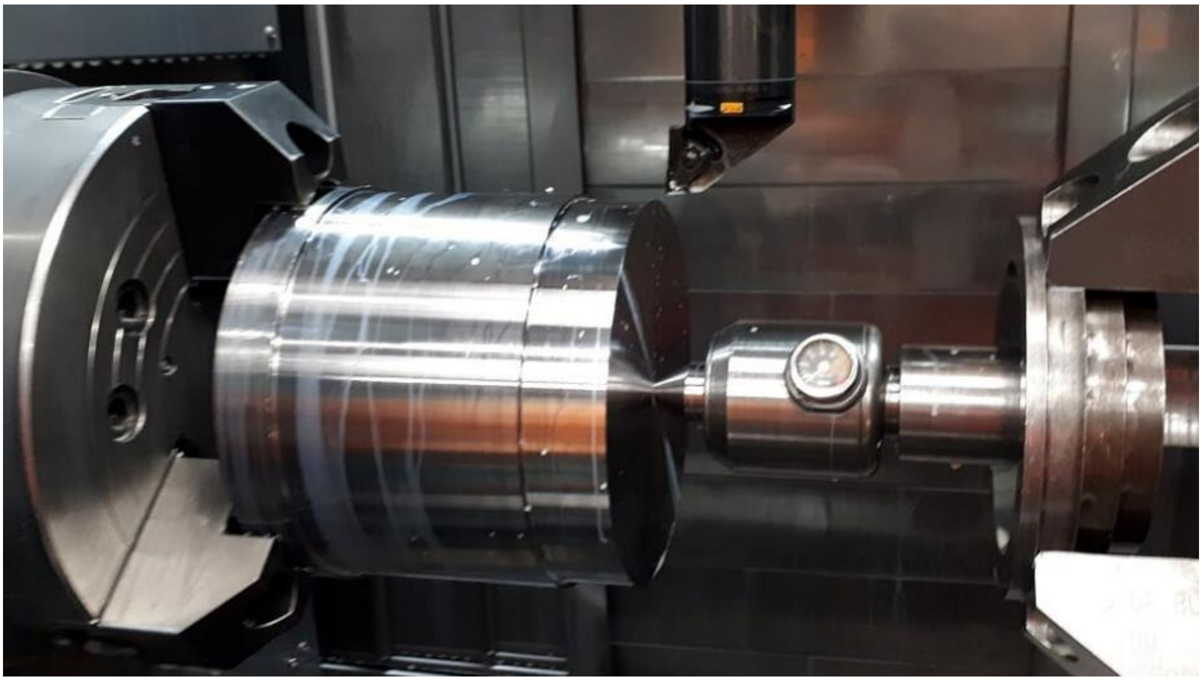


Figure 3.4.3.3 Roughing experimentation set up during machining.

Experimentation followed the following procedure:

- new roughing cutting insert with unused cutting edge was mounted in the toolholder,
- sequence with set cutting parameters was machined,
- during machining of the sequence, the value of machine power consumed was taken by looking at machine's power indicator,
- the tool was put in the initial position in the NC program,
- a machine stop M01 was called,
- door of the machine was manually opened,
- chip sample was taken and labelled,
- chip catching surface was cleaned and the rest of the chips were put in chip conveyer,
- door of the machine was closed,
- next cutting sequence was machined, then procedure was repeated till all sequences for given tool were machined
- next cutting roughing insert was mounted and procedure of chip sampling was repeated until all chosen roughing cutting inserts were tested.

Every pass with fixed depth of cut was divided into 4 zones that were machined consecutively

Chips from every experiment were saved in a labelled zip lock bag and a drop of oil was added to protect chips from corrosion.

Figure 3.4.3.4 Chip samples in labelled zip lock bags after adding oil to protect chips from corrosion.

3.4.4 Results of chip fragmentation during roughing

To evaluate the results of chip fragmentation, chip fragmentation diagrams were created.

All photos of chips were taken from 15 cm distance from the camera, zoom 80%.

The setup for picture taking of chips is shown on the following picture.

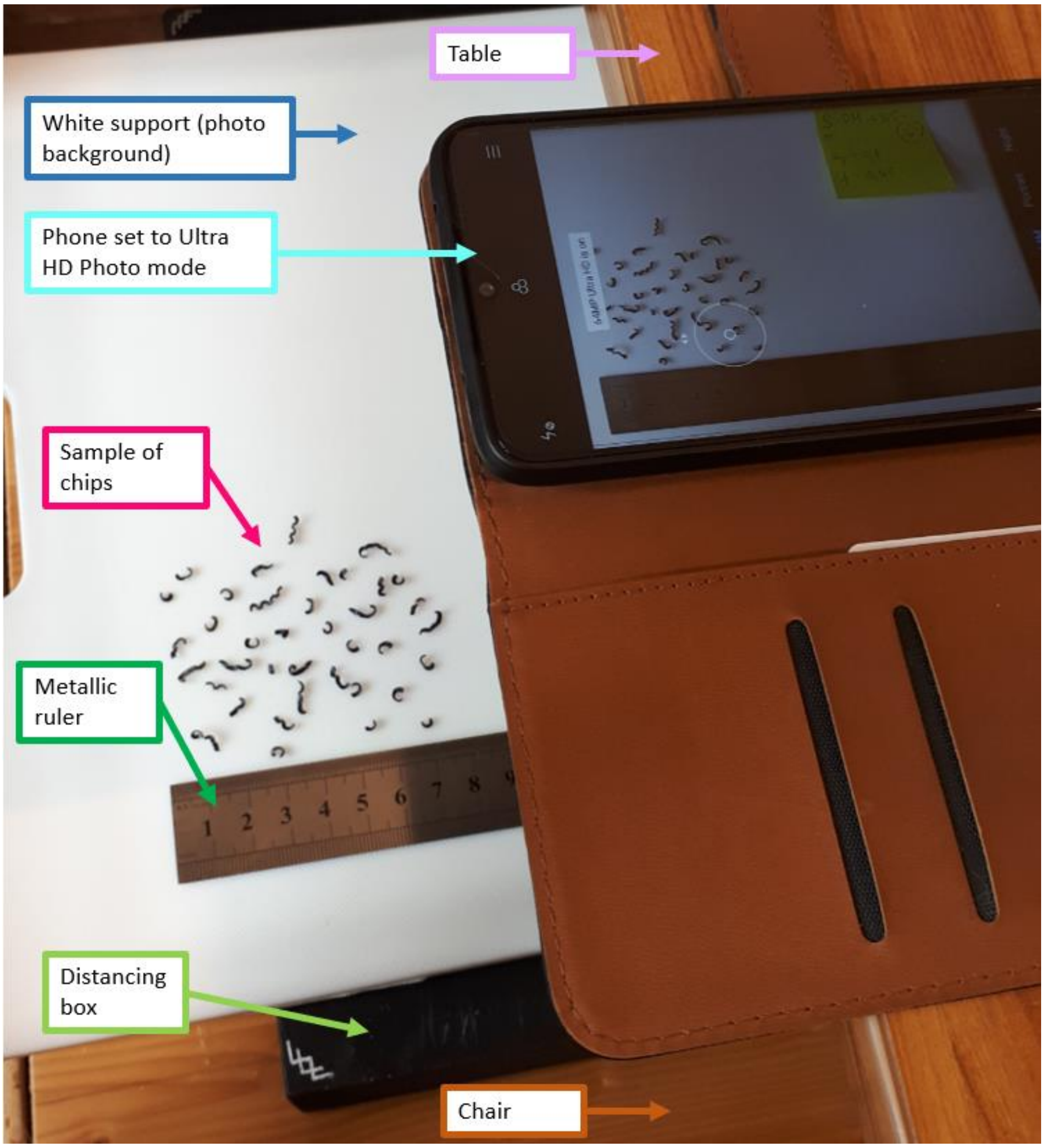


Figure 3.4.4.1 Set up for taking reference photos of chips.

The distance between the white support and the camera was measured as 15 cm.

Some chips were too long and their photo was taken from a large distance, usually the photo was not taken on the same background and is recognisable.

Example of a photo of a chip sample taken is shown in the figure below.

Figure 3.4.4.2 Photo of chip sample, retouched for contrast and brightness.

In every photo a post-it with identification number of the experiment was placed to enable easier treatment of data.

All photos of chips were retouched for contrast and brightness. Then they were cropped to have only the chip sample in them (while not rescaling). These photos were then inserted into chip fragmentation diagrams.

The chip fragmentation diagrams were created using Affinity Designer program. In the program all pictures were rescaled to same percentage (80%).

The repeatable setup and no rescaling ensured that photos were to scale one to another in one diagram.

Results of chip fragmentations during roughing with CNMG 16 geometry of cutting inserts are shown on following figures.

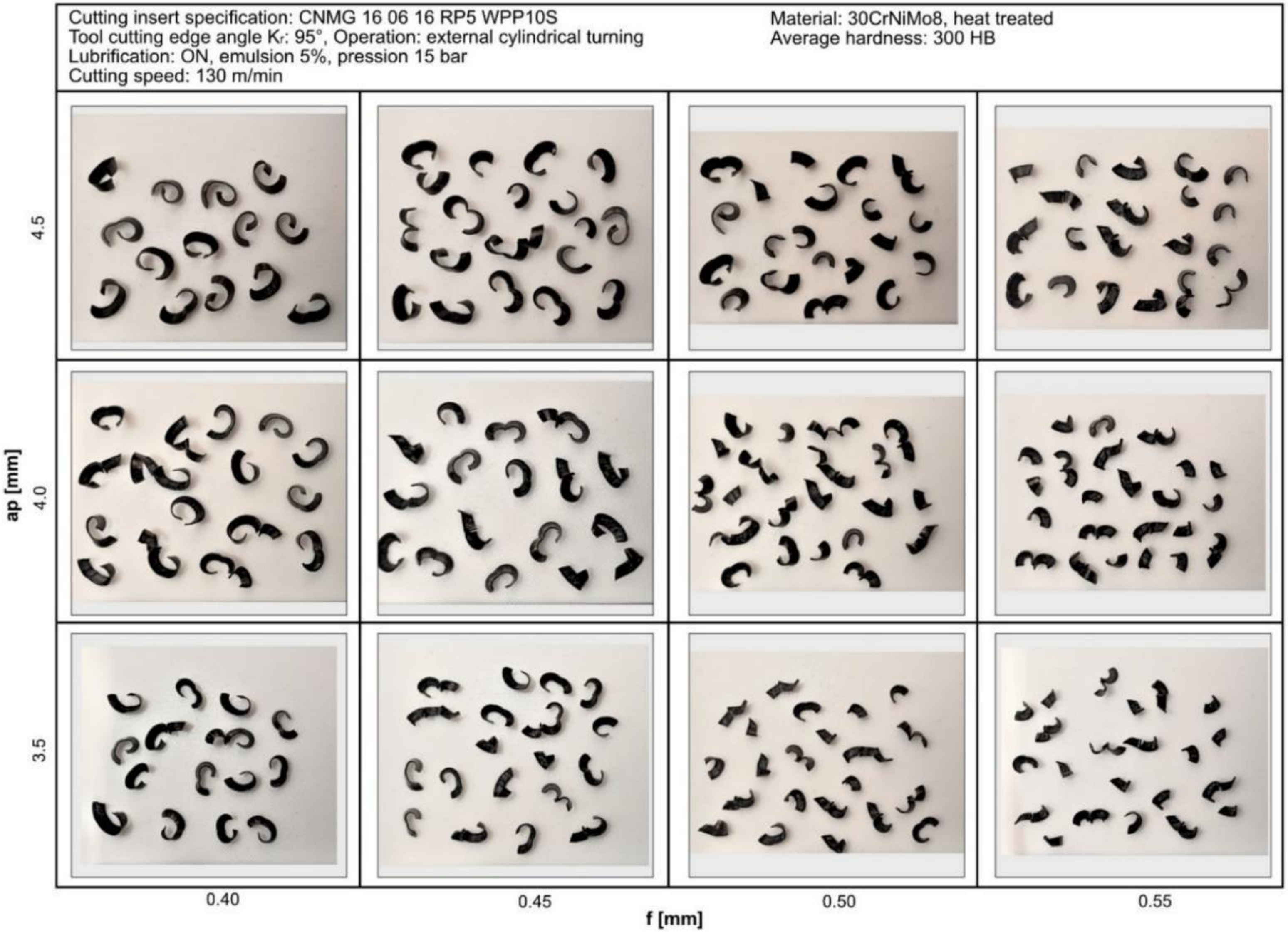


Figure 3.4.4.3 Chip fragmentation for Walter roughing indexable cutting insert CNMG 16 06 16 RP5 WPP10S.

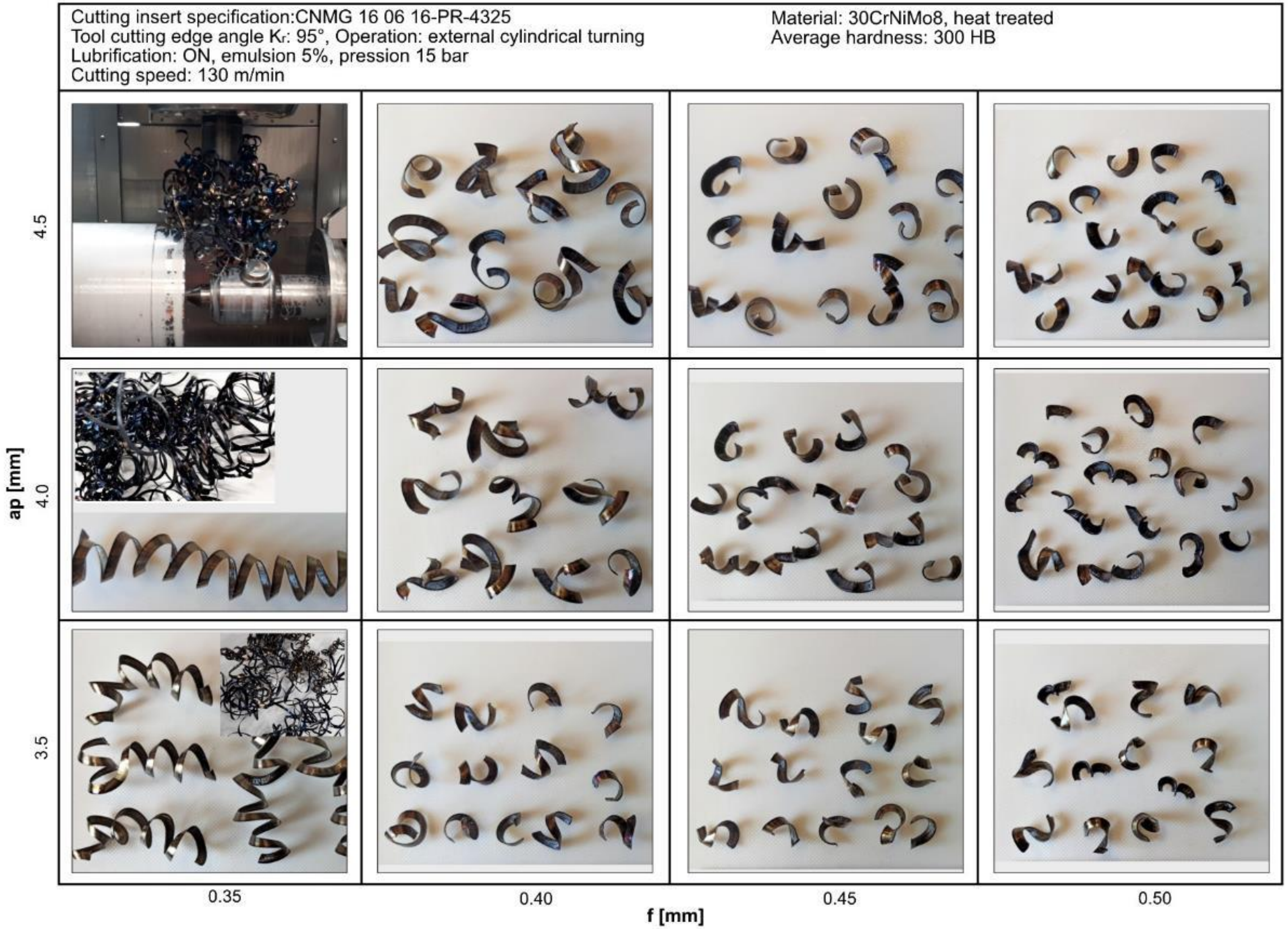


Figure 3.4.4.4 Chip fragmentation for Sandvik roughing indexable cutting insert CNMG 16 06 16 PR 4325.

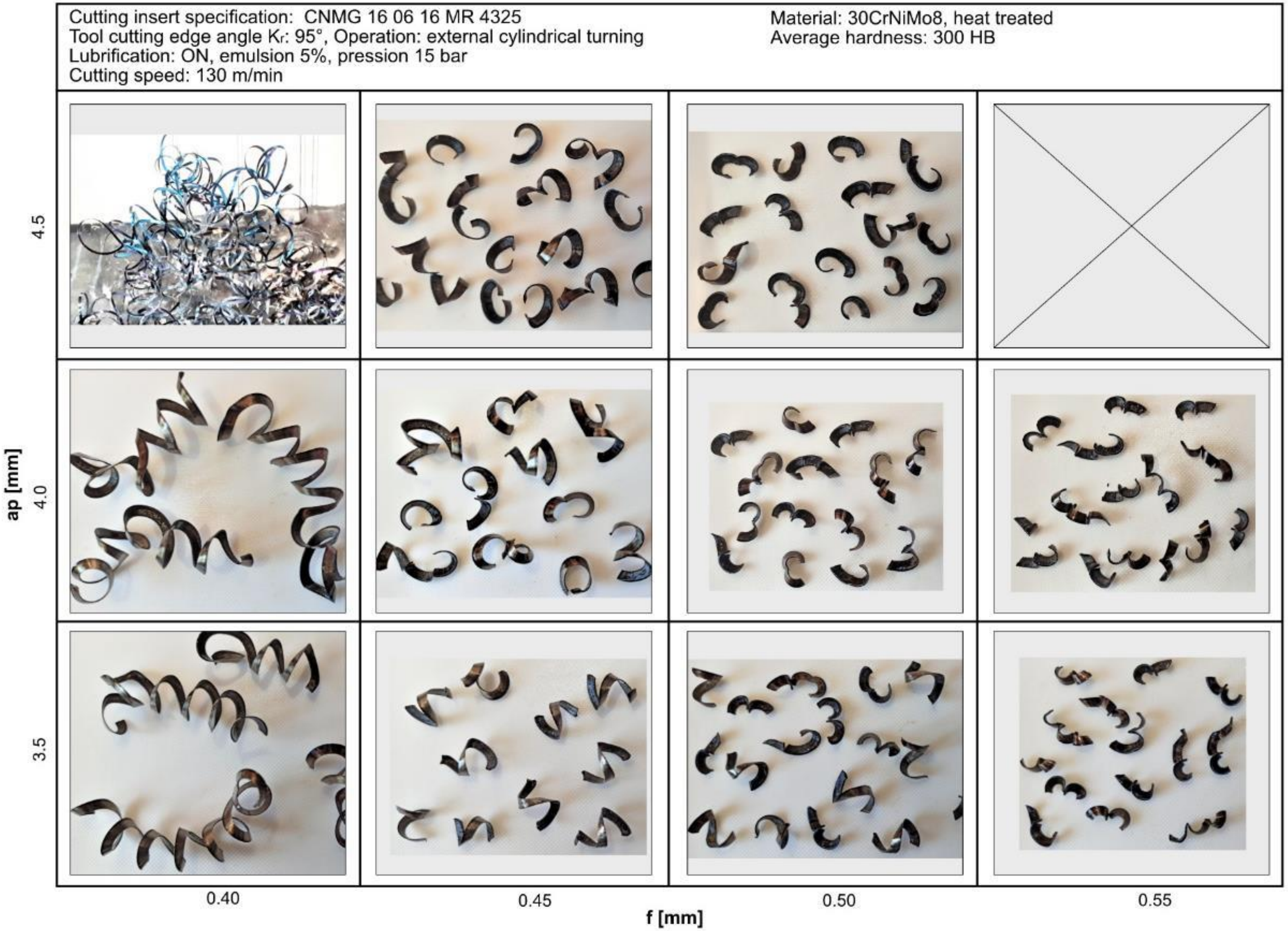


Figure 3.4.4.5 Chip fragmentation for Sandvik roughing indexable cutting insert CNMG 16 06 16 MR 4325.

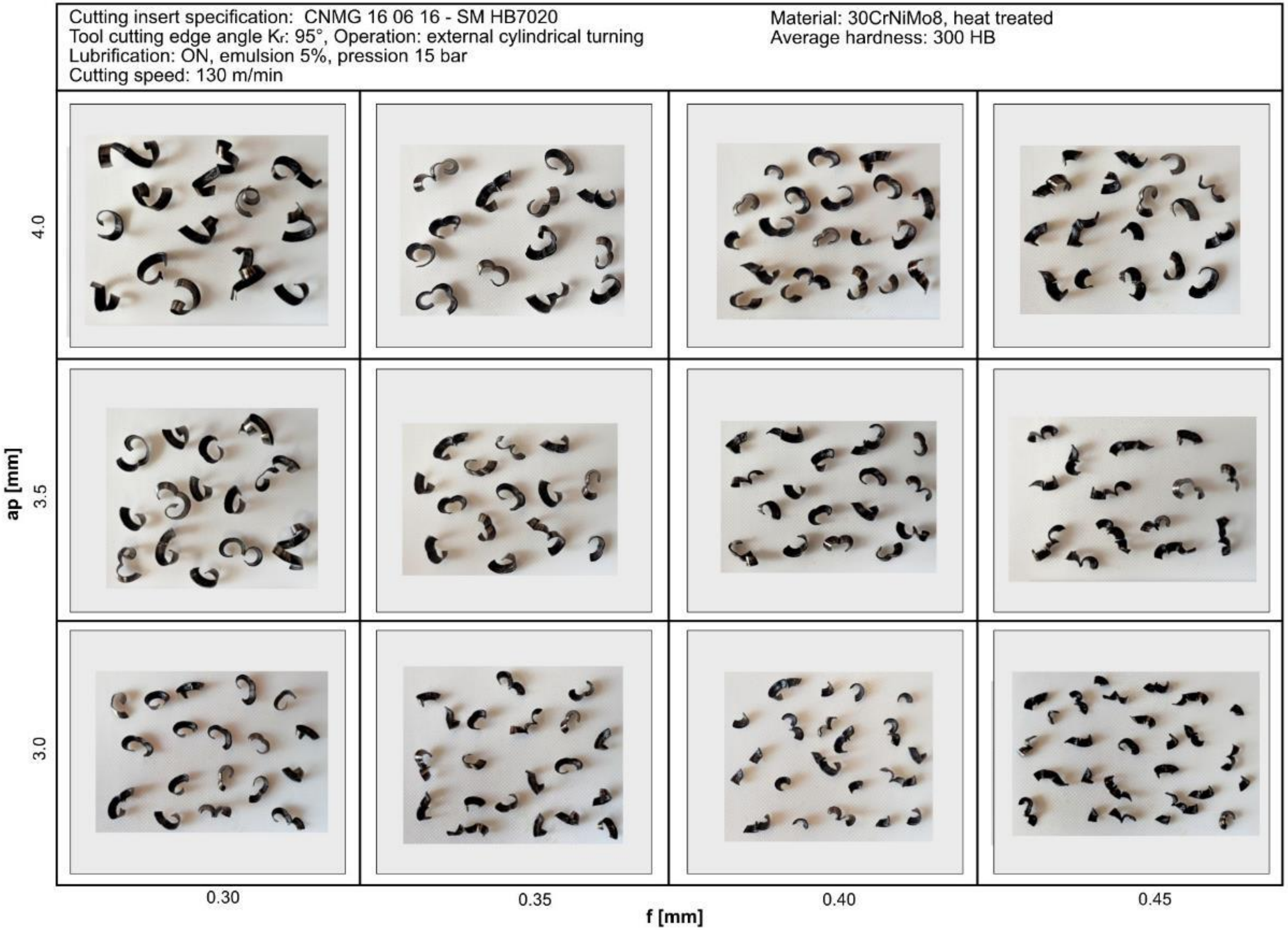


Figure 3.4.4.6 Chip fragmentation for Garant semi-roughing indexable cutting insert CNMG 16 06 16 SM HB7020.

3.4.5 Results of specific cutting pressure k_c

During experimentations of roughing, values of power consumed by the machine were taken at every cut segment.

Power consumed by the machine can be calculated as previously stated in the theoretical analysis [19]:

$$P_{mc} = \frac{P_c}{\mu} = \frac{k_c \cdot f \cdot a_p \cdot v_c}{60 \cdot 1000 \cdot \mu} \quad (13)$$

Where:

- k_c … specific cutting pressure [N/mm^2],
- P_c … cutting power [kW],
- P_{mc} … power consumed by the engine of the machine during machining [kW],
- μ … efficiency [%].

Efficiency was considered 100%.

By measuring the consumed power, the specific cutting pressure can be determined experimentally. By simple inversion of the equation above, following equation can be obtained:

$$k_c = \frac{P_c \cdot 60 \cdot 1000}{f \cdot a_p \cdot v_c} \quad (14)$$

Specific cutting pressure is a indication of how easily the material can be cut. It a function of multiple influences, most importantly workpiece material, tool and cutting conditions.

Workpieces are harder closer to the extremity. The cutting force does not get higher with increasing hardness if between values 30 to 50 HRC [76].

Slight variation of workpiece hardness depending on diameter was not taken to consideration for the computation of specific cutting pressure.

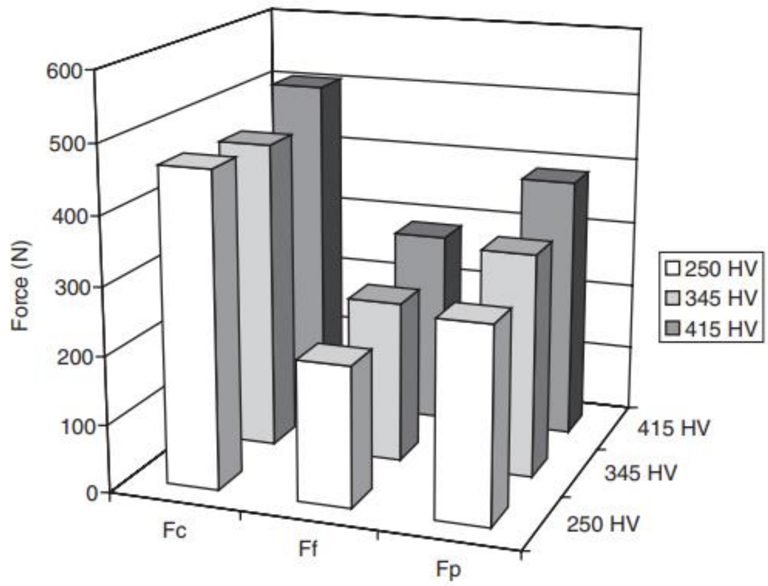


Figure 3.4.5.1 Effect of material hardness on turning forces [76].

Calculated valued of specific cutting pressure are listed in the table below.

Table 3.4.5.1 Calculation of specific cutting pressure for experimentation of turning.

Ref.	insert	phase	exp. reference	ap (mm)	f (mm)	vc (mm)	d machined (mm)	%Pc	Pc (KW)	Kc (MPa)
x	X	Workpiece 3B	X	X	X	X	253			
x	Garant	Oxidized layer	X	3	0.4	130	253			
x	Garant	Oxidized layer	X	3	0.4		253			
Sandvik PR	CNMG 16 06 16 PR 4325	Roug., pass 1,	S-PR-1	3.5	0.4	130	246	72	13.32	5018.5
		Roug., pass 1,	S-PR-2		0.4			69	12.77	4208.2
		Roug., pass 1,	S-PR-3		0.5			76	14.06	4120.1
		Roug., pass 1,	S-PR-4		0.5			82	15.17	4000.9
		Roug., pass 2,	S-PR-5	4	0.4	130	238	69	12.77	4208.2
		Roug., pass 2,	S-PR-6		0.4			75	13.88	4002.4
		Roug., pass 2,	S-PR-7		0.5			82	15.17	3889.7
		Roug., pass 2,	S-PR-8		0.5			89	16.47	3799.6
		Roug., pass 3,	S-PR-9	4.5	0.4	130	229	74	13.69	4011.7
		Roug., pass 3,	S-PR-10		0.4			82	15.17	3889.7
		Roug., pass 3,	S-PR-11		0.5			88	16.28	3710.5
		Roug., pass 3,	S-PR-12		0.5			96	17.76	3643.1
Sandvik MR	CNMG 16 06 16 MR 4325	Roug., pass 1,	S-MR-1	3.5	0.4	130	222	63	11.66	3842.3
		Roug., pass 1,	S-MR-2		0.5			68	12.58	3686.4
		Roug., pass 1,	S-MR-3		0.5			75	13.88	3659.3
		Roug., pass 1,	S-MR-4		0.6			80	14.8	3548.5
		Roug., pass 2,	S-MR-5	4	0.4	130	214	69	12.77	3682.2
		Roug., pass 2,	S-MR-6		0.5			75	13.88	3557.7
		Roug., pass 2,	S-MR-7		0.5			85	15.73	3628.8
		Roug., pass 2,	S-MR-8		0.6			87	16.1	3376.6
		Roug., pass 3,	S-MR-9	4.5	0.4	130	205	81	14.99	3842.3
		Roug., pass 3,	S-MR-10		0.5			84	7.585	1728.8
		Roug., pass 3,	S-MR-11		0.5			87	16.1	3301.5
		Roug., pass 3,	S-MR-12							
Walter Tools	CNMG 16 06 16-RP5 WPP10S	Roug., pass 1,	W-RP-1	3.5	0.4	130	198		0	0.0
		Roug., pass 1,	W-RP-2		0.5			62	11.47	3361.2
		Roug., pass 1,	W-RP-3		0.5			67	12.4	3269.0
		Roug., pass 1,	W-RP-4		0.6			73	13.51	3238.0
		Roug., pass 2,	W-RP-5	4	0.4	130	190	62	11.47	3308.7
		Roug., pass 2,	W-RP-6		0.5			68	12.58	3225.6
		Roug., pass 2,	W-RP-7		0.5			74	13.69	3159.2
		Roug., pass 2,	W-RP-8		0.6			80	14.8	3104.9
		Roug., pass 3,	W-RP-9	4.5	0.4	130	181	66	12.21	3130.8
		Roug., pass 3,	W-RP-10		0.5			72	13.32	3035.9

		Roug., pass 3,	W-RP-11		0.5			79	14.62	2997.9
		Roug., pass 3,	W-RP-12		0.55			91	16.84	3139.4
Garant	Garant	Roug., pass 1,	G-1	3.5	0.3	130	174	40	7.4	3252.7
		Roug., pass 1,	G-2		0.4			43	7.955	2997.2
		Roug., pass 1,	G-3		0.4			49	9.065	2988.5
		Roug., pass 1,	G-4		0.5			55	10.18	2981.7
		Roug., pass 2,	G-5	4	0.3	130	166	44	8.14	3130.8
		Roug., pass 2,	G-6		0.4			49	9.065	2988.5
		Roug., pass 2,	G-7		0.4			54	9.99	2881.7
		Roug., pass 2,	G-8		0.5			60	11.1	2846.2
		Roug., pass 3,	G-9	3	0.3	130	160		0	0.0
		Roug., pass 3,	G-10		0.4			37	6.845	3008.8
		Roug., pass 3,	G-11		0.4			41	7.585	2917.3
		Roug., pass 3,	G-12		0.5			43		2719.7

Lower specific cutting pressure k_c mean that less energy is required for the cutting. That also signifies longer tool life of the cutting insert.

In the graphic below, tested cutting insert are compared for fixed values of feed at different depths of cut.

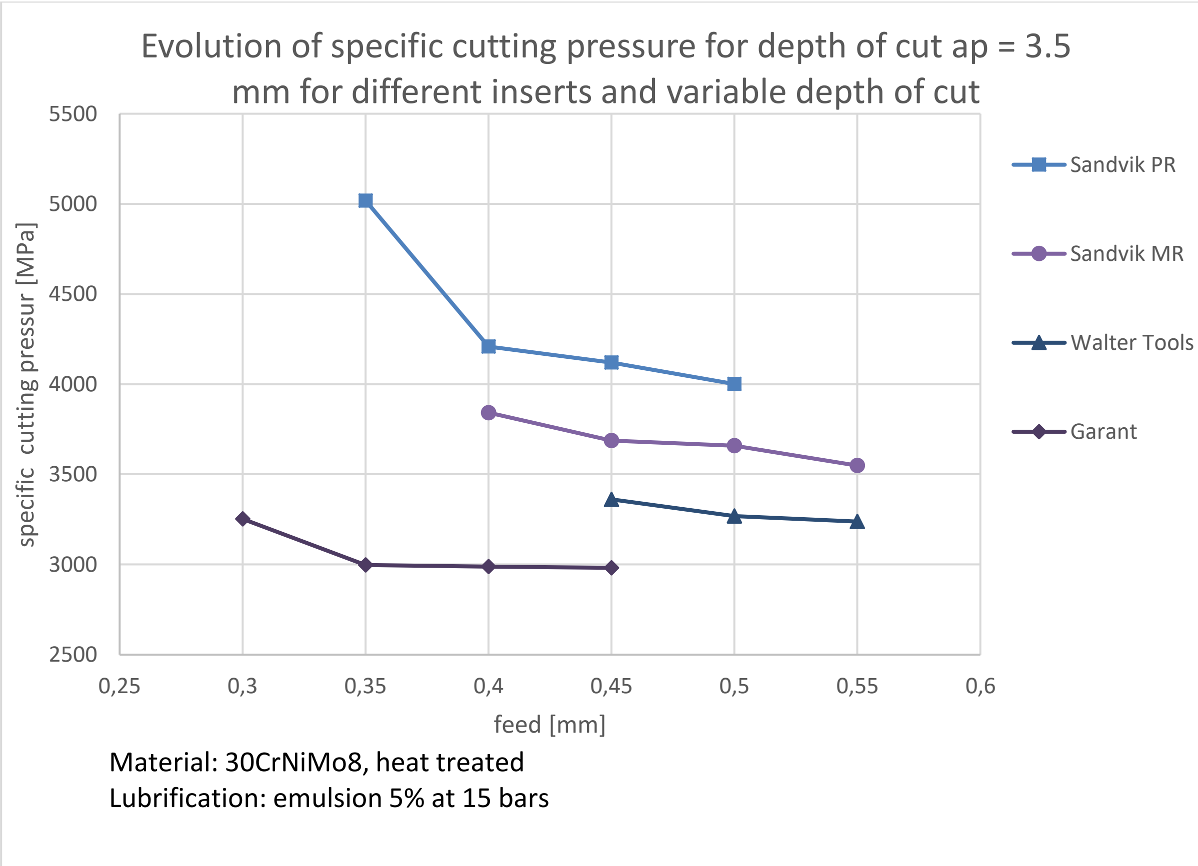


Figure 3.4.5.2 Values of specific cutting pressure for depth of cut a_p= 3.5 mm.

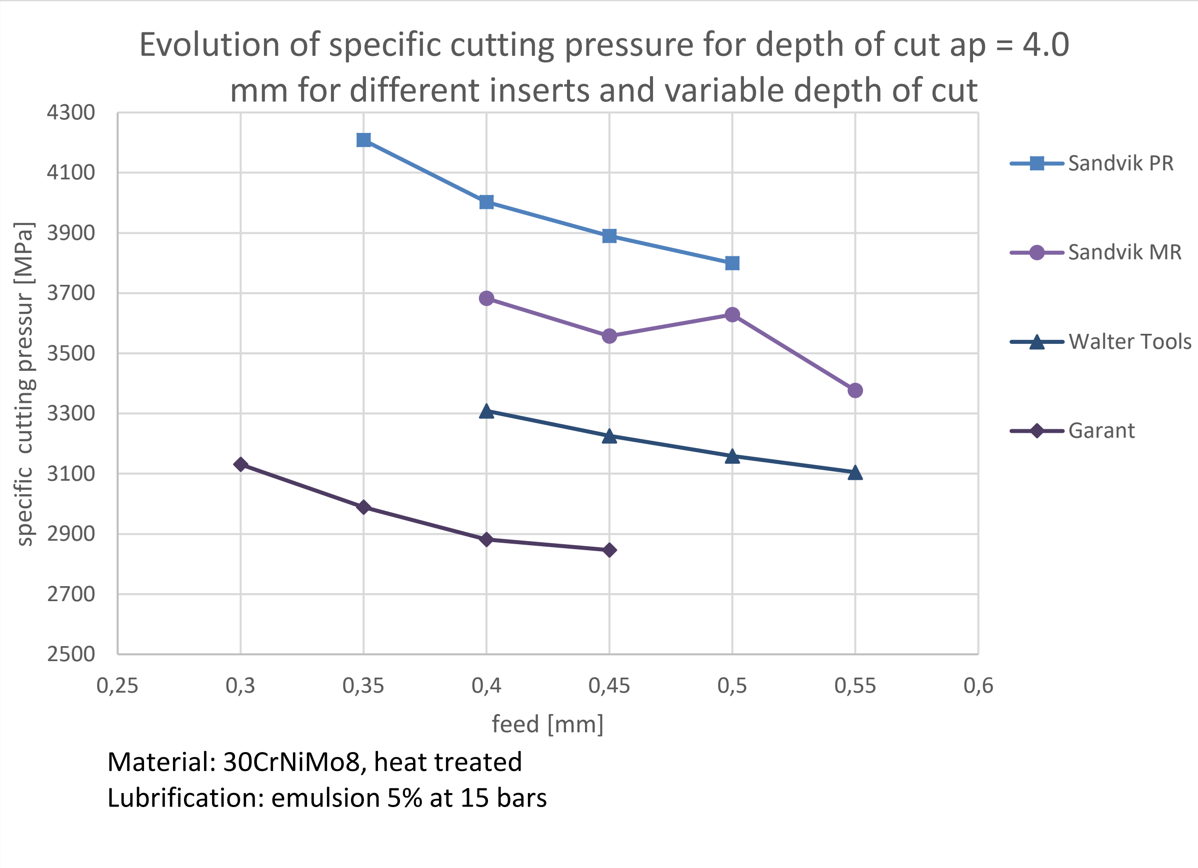


Figure 3.4.5.3 Values of specific cutting pressure for feed a_p= 4.0 mm.

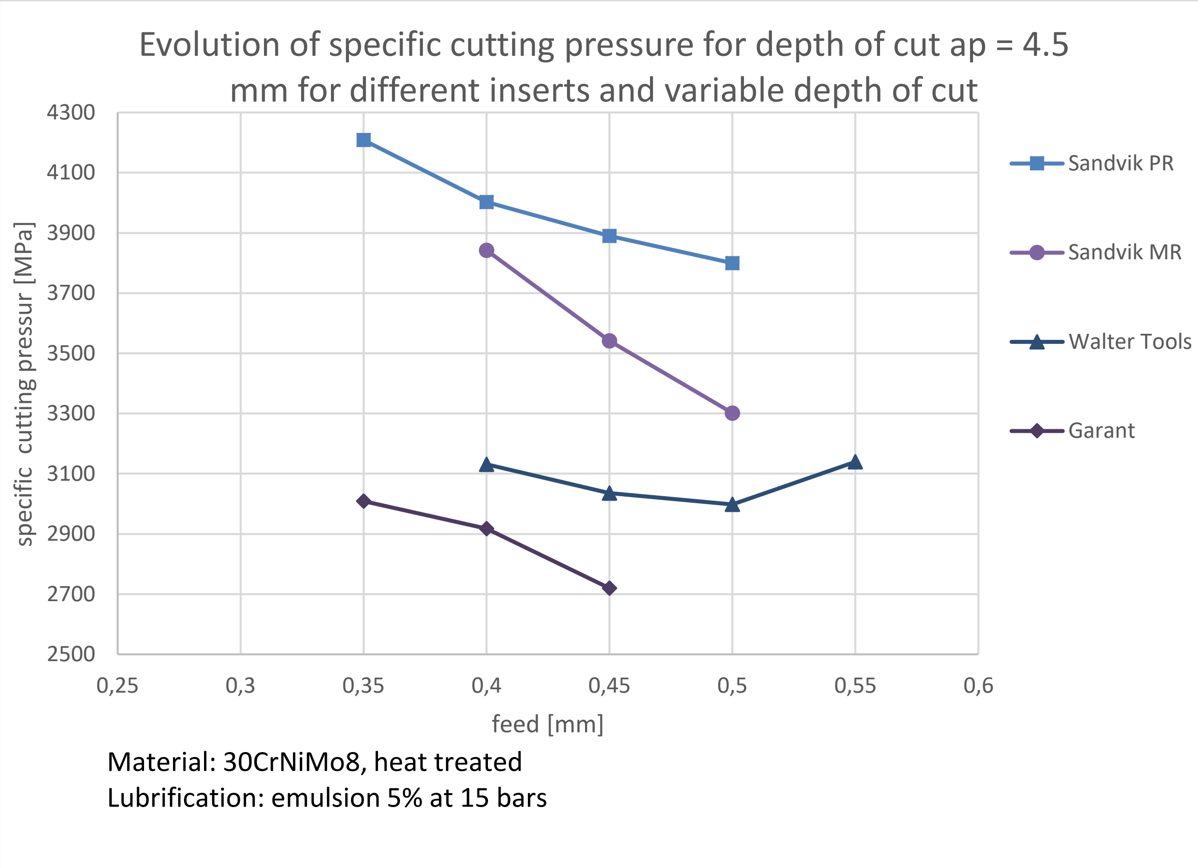


Figure 3.4.5.4 Values of specific cutting pressure for feed a_p= 4.5 mm.

The lower is the alure of the values of k_c for the inset at the same cutting conditions, the better. Lower cutting forces have important influence on machining costs [77].

The cutting insert from tool fabricant Garant required the lowest cutting energy but was limited with a_p and f maximal, therefore the maximal chip removal rate was limited. Cutting insert allowing larger depth of cut and feed while requiring less power was the cutting insert from Walter Tools.

Roughing grade of the Garant tool should be investigated and compared to the roughing cutting insert from Walter Tools.

3.4.6 Investigation of typical tool wear

Chosen roughing cutting insert was then tested in production on the biggest workpiece HP3. Macroscopic photos of the cutting insert after machining the whole workpiece were taken.

Cutting conditions:

- a_p = 3 mm for first 7 passes, then a_{p} = 4.0mm,
- f = 0.30 mm for first 7 passes, then f =0.45,
- Machining time = 45 min.

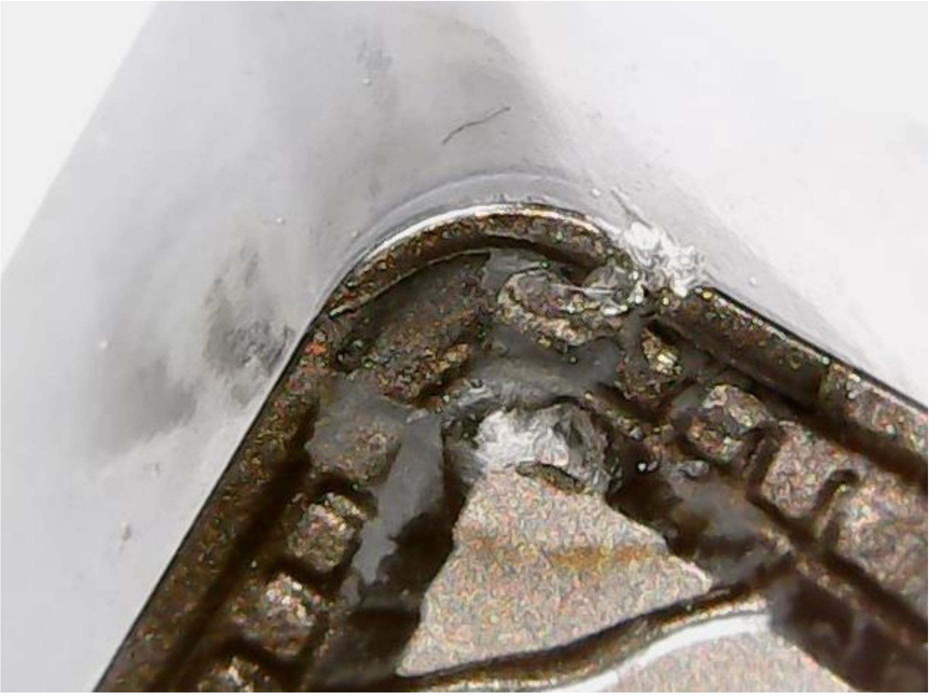


Figure 3.4.6.1 Tool wear typically obtained after roughing operation of the locking bolt.

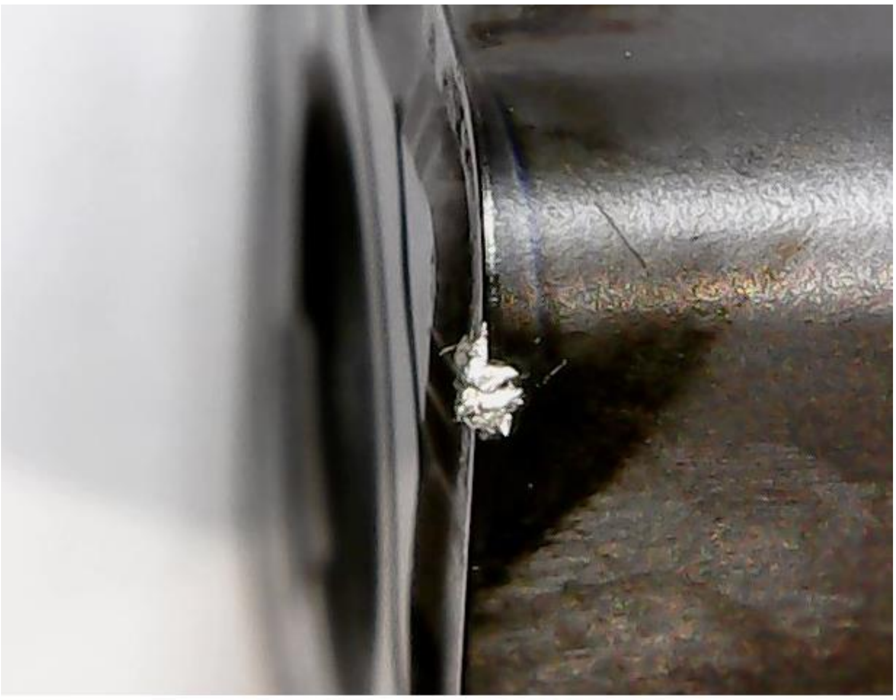


Figure 3.4.6.2 Groove shape wear typically obtained after roughing operation of the locking bolt.

The tool wear was caused by depth of cut notching.

Notch wear is typical To avoid notch wear small depths of cut should be avoided [22].Using variable depth of cut is recommended to avoid notch wear at one point of the cutting insert. Maximum depth of cut should be used to avoid machining with the nose radius of the insert.

3.4.7 Overall results in roughing

Recommendations for roughing of exterior diameters of the locking bolts are as follows based on the results of the chip fragmentation results and consumed power study.

Table 3.4.7.1 Recommended cutting parameters based on experimentations of roughing

General information			Cutting conditions recommended based on experimentations, for material 30CrNiMo8 + QT, workpiece diameter 280 mm and 17kW Turn Mill machine				
application	producer	designation	a_p min (mm)	a_p max (mm)	f min (mm)	f max (mm)	v_c (m/min)
roughing	Walter	CNMG 16 06 16-RP5 WPP10S	3.50	4.50	0.40	0.50	130
roughing	Sandvik	CNMG 16 06 16 PR 4325	3.50	4.50	0.40	0.50	130
roughing	Sandvik	CNMG 16 06 16 MR 4325	4.00	4.50	0.50	0.50	130
semi-finishing	Garant	CNMG 16 06 16 - SM HB7020	3.00	4.00	0.3	0.45	130

For roughing of external diameter regularise new cutting insert CNMG 16 06 16 RP5 WPP10S by Walter Tools and use following cutting conditions:

- a_p = 3.5-4.5 mm depending on machined diameter,
- f_{max} = 0.50 mm,
- v_c = 140 m/min (use as depart value and follow by studying tool life in production with different v_c).

Original cutting parameters were:

- $a_{p, original}$ = 3.0 mm,
- $f_{original}$ = 0.32 mm,
- v_c = 180 m/min.

Original cutting parameters resulted in machining time per operation of roughing $T_{roughing,HP3, original}$ = 18 min 59 sec.

Considering new cutting parameters:

- $a_{p, new}$ = 4.5 mm,
- f_{new} =0.5 mm
- v_c = 130 m/min.

The improved machining time per operation of roughing was $T_{roughing,HP3, new, vc130}$ = 10 min 29 sec. The machining time using the cutting speed 130 m/min presents decrease of machining time by 45% compared to the original cutting sequence.

Considering new cutting parameters:

- $a_{p, new}$ = 4.5 mm,
- f_{new} =0.5 mm
- v_c = 140 m/min.

The improved machining time per operation of roughing was $T_{roughing,HP3, new, vc130}$ = 9 min 26 sec. The machining time using the cutting speed 140 m/min presents decrease of machining time by 51% .

Considering new cutting parameters:

- $a_{p, new}$ = 4.5 mm,
- f_{new} =0.5 mm
- v_c = 150 m/min.

The improved machining time per operation of roughing would be $T_{roughing,HP3, new, vc150}$ = 8 min 49 sec. The improved machining time per operation of roughing was $T_{roughing,HP3, new, vc130}$ = 9 min 26 sec. The machining time using the cutting speed 150 m/min presents decrease of machining time by 54% .

To determine the optimal cutting speed, it is recommended to perform a study of tool life in production using different cutting speeds.

For locking of diameters larger than 280mm, lower cutting parameters must me used to fit in power limits of the NC machine. For example, the largest locking bolt HP6 can be performed as follows.

Original cutting conditions for roughing of locking bolt HP6 were:

- a_{p1}= 3 mm,
- f_1 =0.3 mm,
- v_c = 180 m/min,
- T = 55 min 13s,
- n_{passes} = 7.

The machining time per operation of roughing was originally $T_{roughing, HP6, original}$ = 55 min 13 sec.

Improved cutting strategy of rouging of locking bolt HP6 are divided into 2 phases, first phase is on the larger part of the workpiece diameter.

Phase 1 of rouging of locking bolt HP6 has following cutting parameters recommended:

- a_{p1}= 3 mm,
- f_1 =0.3 mm,
- v_c = 180 m/min,
- T = 21 min,
- n_{passes} = 7.

Phase 2 of rouging of locking bolt HP6 has following cutting parameters recommended:

- a_{p1}= 4.5 mm,
- f_1 =0.45 mm
- v_c = 140 m/min
- T = 19 min 42 s
- n_{passes} = 9

The two phased roughing of locking bolt HP6 was tested in production with good overall chip fragmentation and acceptable power consumption.

The improved machining time per operation of roughing was $T_{roughing, HP6, new, vc140}$ = 40 min 42 sec. The improved machining time per operation of roughing was $T_{roughing,HP3, new, vc130}$ = 9 min 26 sec. The machining time using the cutting speed 140 m/min presents decrease of machining time by 27% .

3.5 EXPERIMENT 3: CHIP FRAGMENTATION DURING FINISHING AND SEMI-FINISHING WITH GEOMETRY VNMG

Chip fragmentation during the finishing of external diameter and contour was very problematic using the original cutting sequence. Long, thin chips were often stuck around the tool and around the workpiece. Manual intervention was needed to cut the chips and put them in chip conveyor.

3.5.1 Tool and inserts

Tool used was already in use in production, only tool inserts were modified.

Tool used: C6-DVJNL-45065-16.

Tool attachment used: C6-391.01-63 060 (Capto C6 attachment).

Insert geometry: VNMG 16 06

General geometry of the rouging insert was kept the same as previously used, insert with different chip breakers of different manufacturers were tested.

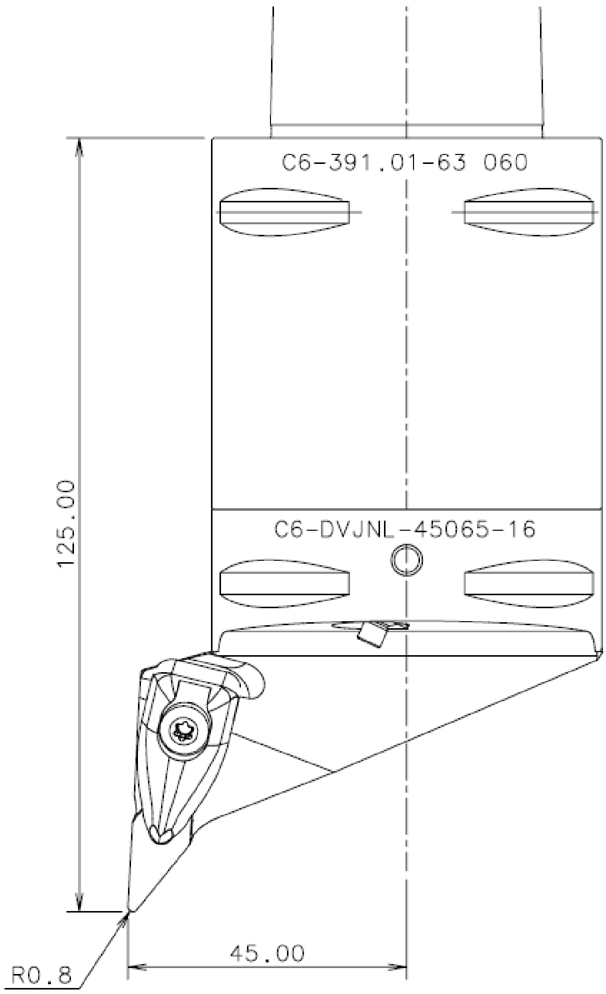
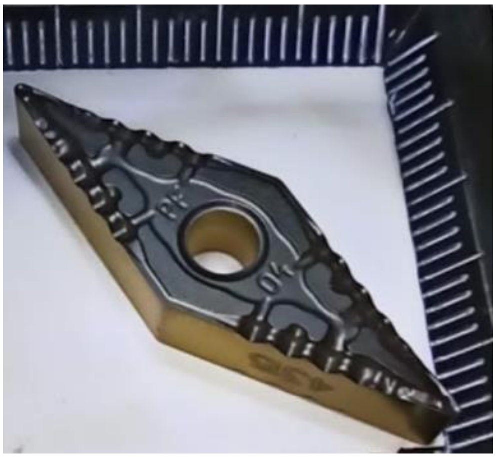
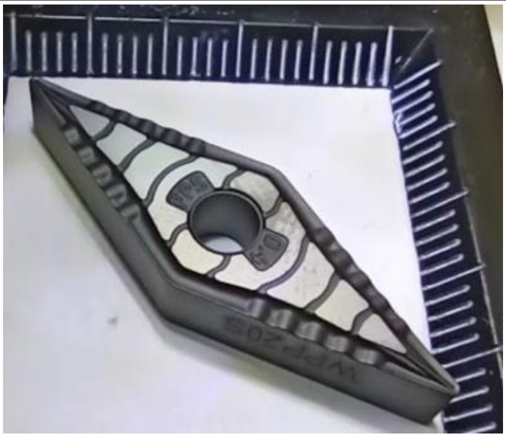


Figure 3.5.1.1 Tool used for finishing.

Cutting insert used for experimentations of finishing are listed in the table below with pictures taken to show differences between chip breakers and overall look of the inserts.

Table 3.5.1.1 Cutting insert used for experimentations of finishing.

General information of cutting inserts VNMG 16 04 used for experimentations of finishing			
producer	designation	application	picture
Sandvik	VNMG 16 04 08-PM 4305	semi-finishing	
Sandvik	VNMG 16 04 04-PF 4315	finishing	
Walter	VNMG 16 04 04-FP5 WPP20S	finishing	

3.5.1.1 Cutting parameters

Cutting parameters recommended by producer of the cutting inserts and cutting conditions used during the experimentations are listed in the table below.

Table 3.5.1.2 Cutting parameters recommended by insert producer and cutting conditions used during experimentations of finishing.

General information			Application limits				Principle application		Recommended by producer			Values during experimentations							
producer	designation	Product information	a_p min (mm)	a_p max (mm)	f min (mm)	f max (mm)	v_c min (m/min)	v_c max (m/min)	a_p (mm)	f (mm)	v_c (m/min)	a_p 1 (mm)	a_p 2 (mm)	a_p 3 (mm)	f1 (mm)	f2 (mm)	f3 (mm)	f4 (mm)	v_c (m/min)
Sandvik	VNMG 16 04 08-PM 4305	producer	0.5	4	0.15	0.50	380	590	1.9	0.3	199	0.8	1.6	2.4	0.15	0.25	0.35	0.45	180
Sandvik	VNMG 16 04 04-PF 4315	producer	0.25	0.50	0.07	0.30	430	590	0.339	0.15	219	0.3	0.6	0.8	0.10	0.15	0.20	0.25	180
Walter	VNMG 16 04 04-FP5 WPP20S	producer	0.1	1.5	0.04	0.22	x	x	0.312	0.11	140	0.4	0.6	0.8	0.09	0.12	0.15	0.20	180

3.5.2 Experimentations

Experimentation of finishing and semi-finishing with insert geometry VNMG followed the experiments of roughing on the same workpiece explained in the previous chapter.

The experimentations of finishing followed the same procedure as roughing experimentations:

- new cutting insert with unused cutting edge was mounted in the toolholder,
- sequence with set cutting parameters was machined,
- during machining of the sequence, the value of machine power consumed was taken by looking at machine's power indicator,
- the tool was put in the initial position in the NC program,
- a machine stop M01 was called,
- door of the machine was manually opened,
- chip sample was taken and labelled,
- chip catching surface was cleaned and the rest of the chips were put in chip conveyer,
- door of the machine was closed,
- next cutting sequence was machined, then procedure was repeated till all sequences for given tool were machined
- next cutting finishing insert was mounted and procedure of chip sampling was repeated until all chosen finishing cutting inserts were tested.

Every cutting sequence corresponded to one of four zones to which the workpiece length was divided. Every pass of the tool was divided into 4 zones, each with different feed.

CAM program in software Esprit and tool trajectories for finishing are displayed in the figure below.

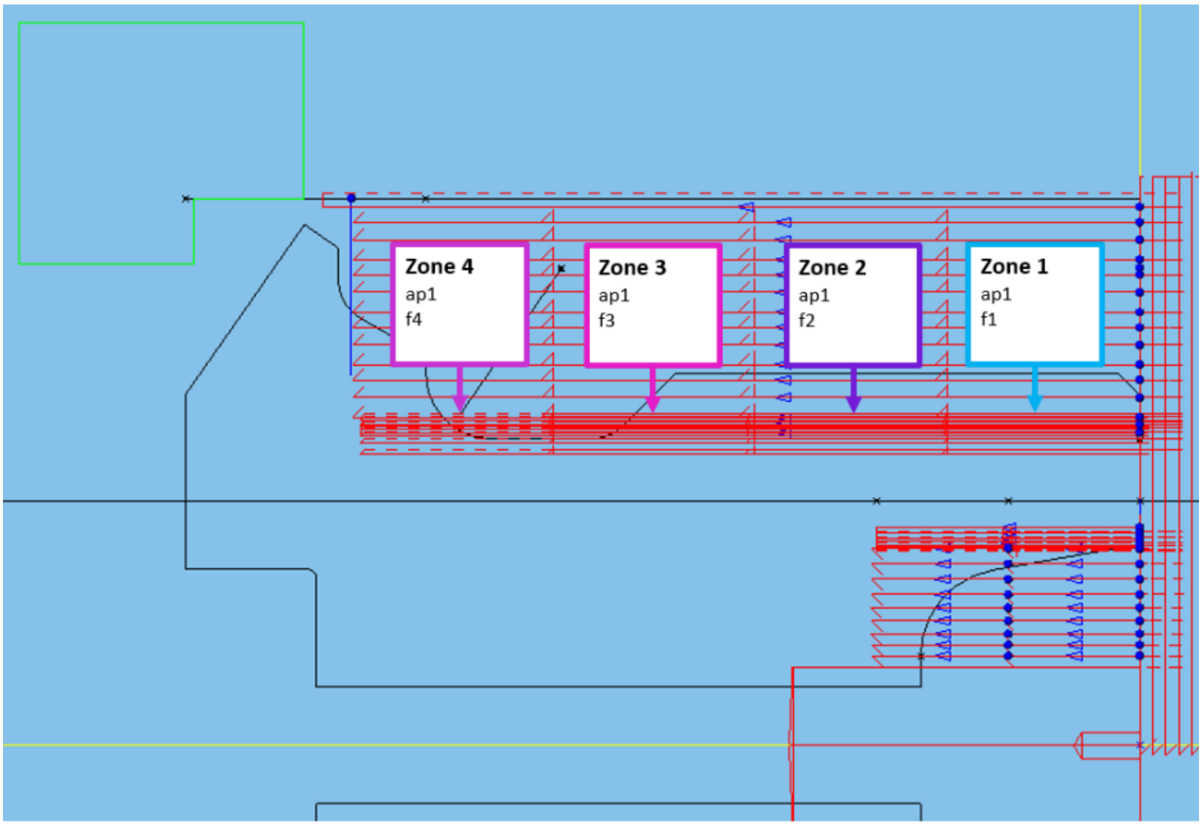


Figure 3.5.2.1 Esprit CAM program showing experimentation of finishing with 4 zones of different feeds.

In the example shown in the figure above, the depth of cut is the same for all 4 zones, but feed varies. Firstly, the zone 1 was machined, the tool was called to its original position and machine was stopped to take out sample of chips. Then zone 2 was machined and so on till zone 4. Then at the next pass, another value of depth of cut was fixed for the next 4 machined segments in zones 1 to 4.

As for the experimentation of roughing, the workpiece with designation 2C was used.

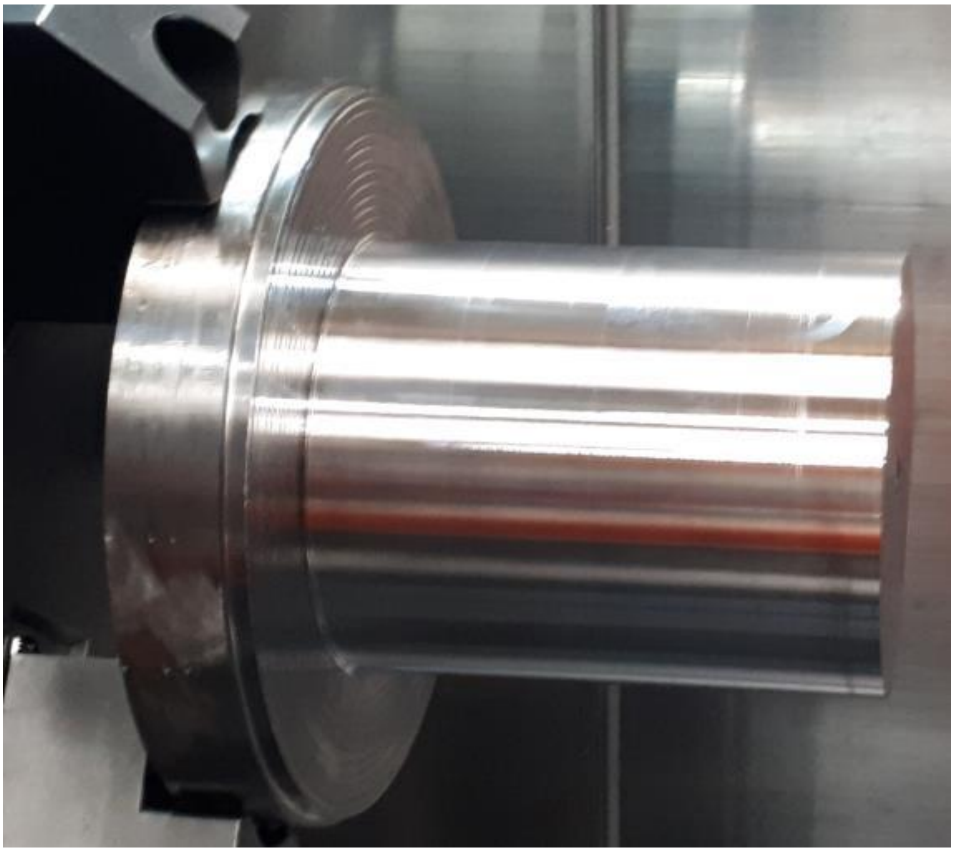


Figure 3.5.2.2 Workpiece after roughing experimentations and before finishing experimentations.

3.5.2.1 **Results: chip fragmentation during finishing and semi-finishing**

The photos of chip samples were taken the same way using the same set up as described in previous chapter concerning experimentation of roughing.

Photos of chips taken from 15 cm distance from the camera.

Photos were retouched to adjust brightness and contrast, cropped and zoomed to 200% for the diagrams.

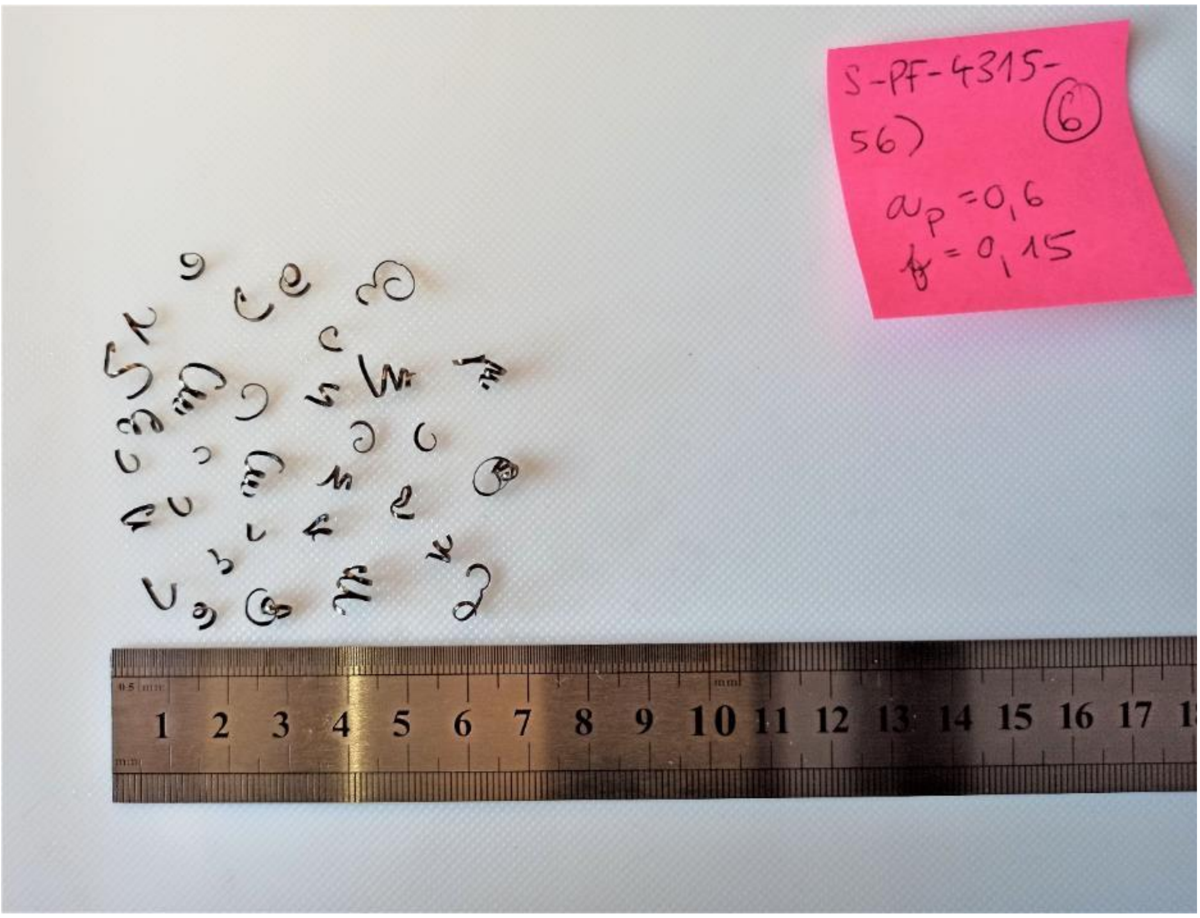


Figure 3.5.2.3 Example of photo of sample of chips taken for the finishing operation retouched, before cropping and rescaling.

Results of chip fragmentations during roughing with CNMG 16 geometry of cutting inserts are shown on following figures. It should be noted that the diagrams are downsized.

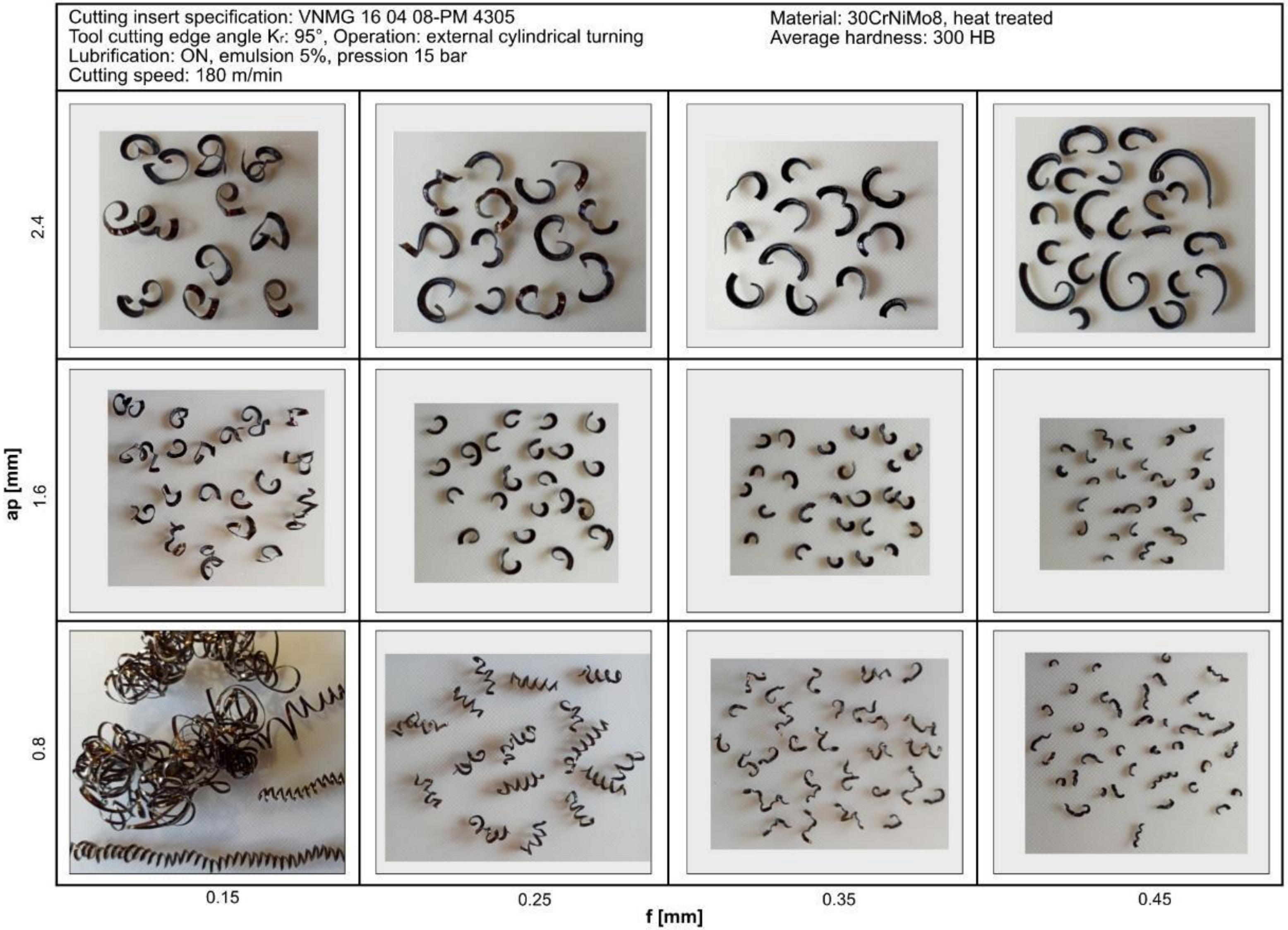


Figure 3.5.2.4 Chip fragmentation for semi-finishing with Sandvik indexable cutting insert VNMG 16 04 08-PM 4305.

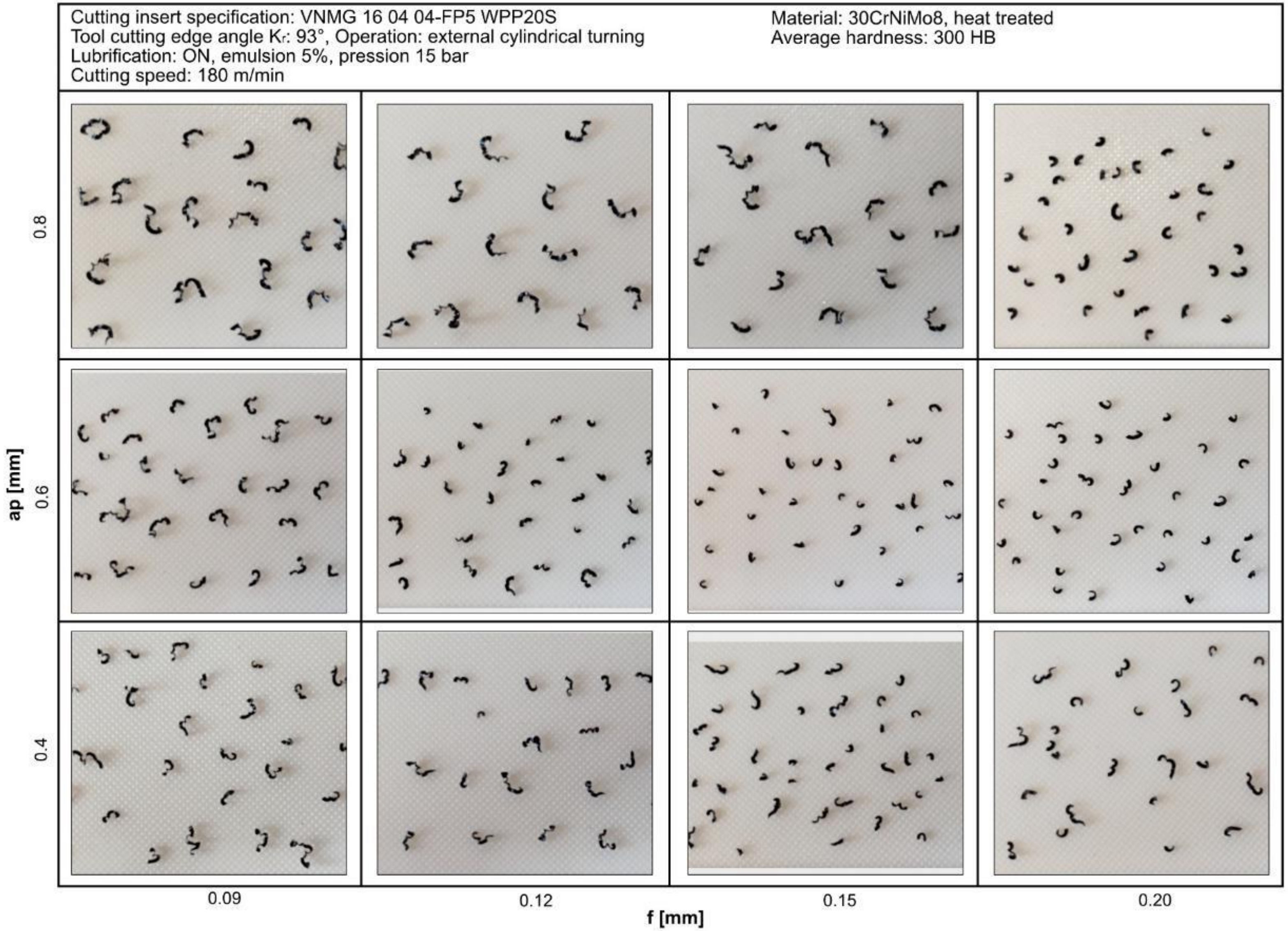


Figure 3.5.2.5 Chip fragmentation for finishing with Walter indexable cutting insert VNMG 16 04 04-FP5 WPP20S.

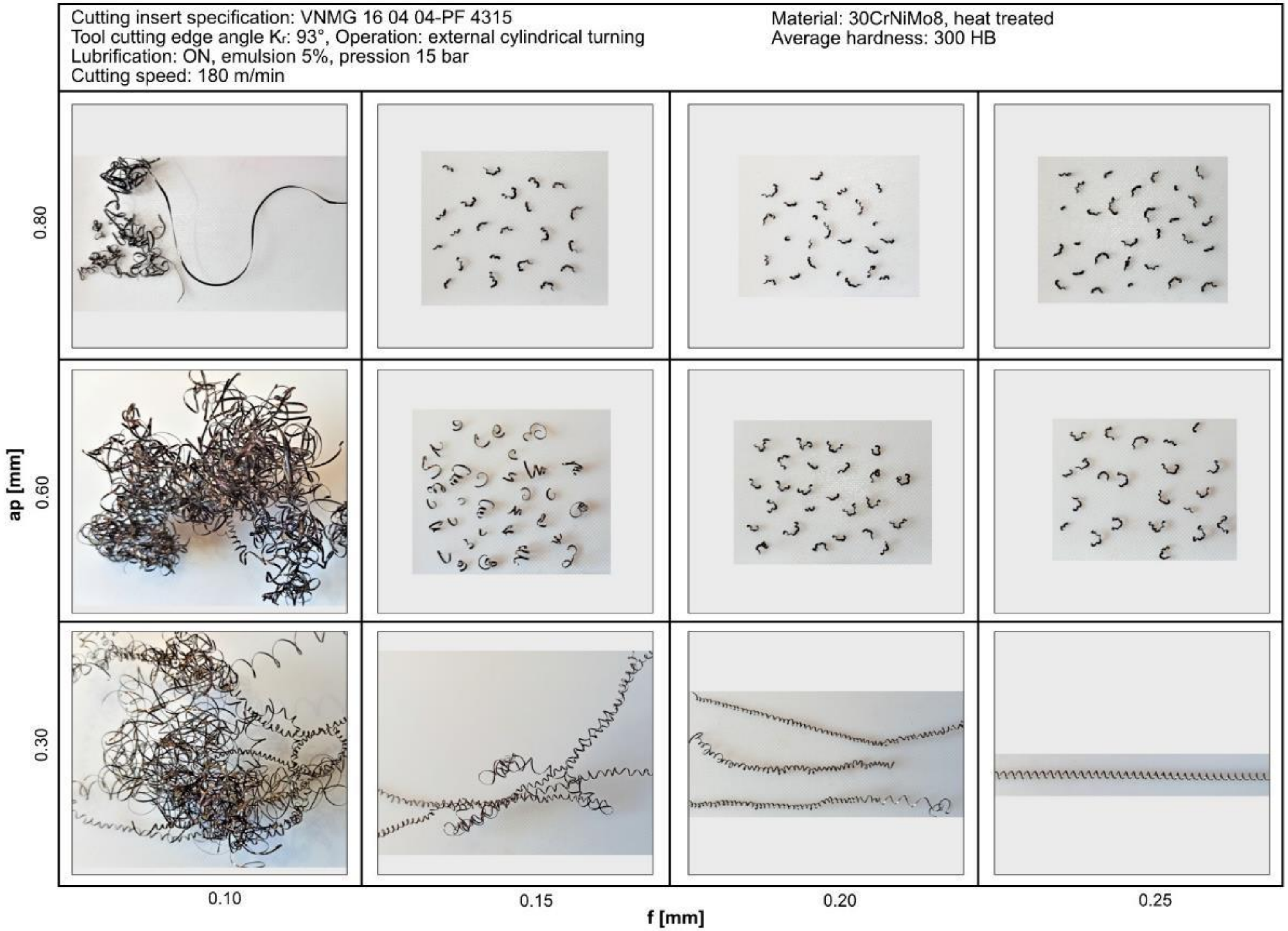


Figure 3.5.2.6 Chip fragmentation for finishing with Sandvik indexable cutting insert VNMG 16 04 04-PF 4315.

3.5.3 Surface roughness in semi-finishing

In original cutting sequence, only finishing cutting insert was used after roughing.

All feed for finishing tools had sufficient roughness lower than Ra = 3.2 µm.

Because the value Ra = 3.2 µm is achievable also with semi-finishing cutting inserts while possibly being more efficient in material removal rate, application of semi-finishing insert was considered and tested.

Surface roughness after semi-finishing with different feeds was tested. In the figure below, workpiece with 4 zones of different roughness can be seen. Each zone was machined with different feed with the same tool VNMG 16 04 08-PM 4305

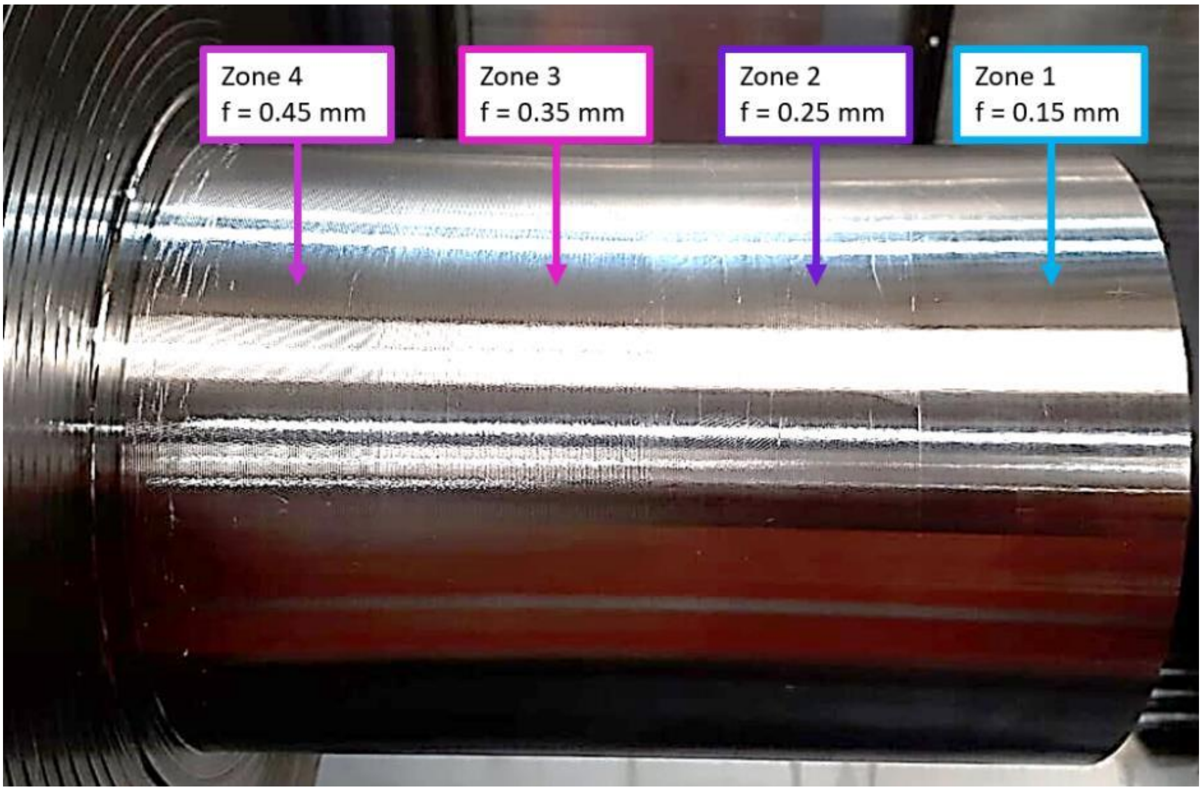


Figure 3.5.3.1 Zones of surface roughness measurements.

Figure 3.5.3.2 Measurement of surface roughness with a roughness tester.

Results of surface roughness during semi-finishing in different values of feed are displayed in the table below.

Table 3.5.3.1 Results of arithmetical surface roughness measured with roughness tester for semi-finishing cutting insert at different values of feed.

Cutting insert	Zone	v_c (m/min)	a_p (mm)	f (mm)	Ra (µm)
VNMG 16 04 08-PM 4305	1	180	2.4	0.15	1.449
	2			0.25	2.045
	3			0.35	4.769
	4			0.45	7.832

Only the first two zones had acceptable roughness. It can be concluded that in case of implementing of this insert, the value of feed should be kept at f = 0.25mm or a value between f= 0.25 and f = 0.35 may be tested and the obtained verified for roughness.

3.5.4 Overall results in finishing

Recommendations for finishing of exterior diameters of the locking bolts are as follows based on the results of the chip fragmentation results and consumed power.

Table 3.5.4.1 Recommendations for cutting condition during finishing of locking bolts based on experimentations.

General information			Cutting conditions recommended based on experimentations, for material 30CrNiMo8 + QT and 17kW Turn Mill machine, for Ra = 3.2				
application	producer	designation	ap min (mm)	ap max (mm)	f min (mm)	f max (mm)	vc min (m/min)
semi-finishing	Sandvik	VNMG 16 04 08-PM 4305	0.80	1.60	0.25	0.25	180
finishing	Sandvik	VNMG 16 04 04-PF 4315	0.60	0.80	0.15	0.25	180
finishing	Walter	VNMG 16 04 04-FP5 WPP20S	0.40	0.80	0.09	0.20	180

SEMI-FINISHING

The semi finishing cutting insert VNMG 16 04 08-PM 4305 did not have ideal chip fragmentation. An alternative insert should be considered for semi-finishing. Semi-finishing is recommended for the groove of the locking bolt if VNMG geometry is kept. An insert with a different chip breaker might perform better.

Feed during semi-finishing with the tested insert should not exceed f = 0.25 mm if semi-finishing is not followed by finishing to obtain a sufficient surface roughness.

If the cutting insert VNMG 16 04 08-PM 4305 is used, recommended cutting parameters should be used:

- $a_p = 1.6$
- $f_{max} = 0.25$ mm,
- $v_c = 180$ m/min (use as depart value and follow by studying tool life in production with different v_c).

FINISHING

For finishing of external diameter regularise new cutting insert VNMG 16 04 04-FP5 WPP20S by Walter Tools.

For turning profiles, an adapted feed should be used. The study of chip fragmentation considered only cylindrical surface turning with angle $K_r = 93°$. When turning a profile the angle K_r changes. The cutting insert VNMG 16 04 04-FP5 WPP20S had the best chip fragmentation proprieties even at low feeds and is therefore is the most adapted.

Original cutting parameters were:

- $a_{p,\ original}$ = 1 mm,
- $f_{original}$ = 0.30 mm,
- v_c = 200 m/min.

New cutting parameters for new finishing insert VNMG 16 04 04-FP5 WPP20S that are recommended are:

- $a_{p,\ new}$ = 0.8 mm (the tested limit, it may be increased),
- f_{new} = 0.25 (max) (the tested limit, it may be increased),
- v_c = 180 m/min (the tested limit, it may be increased).

3.6 EXPERIMENT 4: BORING

There were significant problems with chip fragmentations during boring in production.

To study this problem; chip fragmentation experimentations were conducted.

In production in original cutting sequence, there was only roughing insert used for both roughing and finishing. That may have been the cause of bad chip fragmentation during the last (finishing) pass with the original cutting insert.

Small feed tested on smaller diameters and higher feeds tested on larger diameters

3.6.1 Tools and inserts

Tool that in normally used for boring for locking bolts was used.

Tool holder: C6-PCNLN-17100-12.

Cutting insert geometry for roughing: CNMG 12 04 12.

Cutting insert geometry for finishing: CNMG 12 04 08.

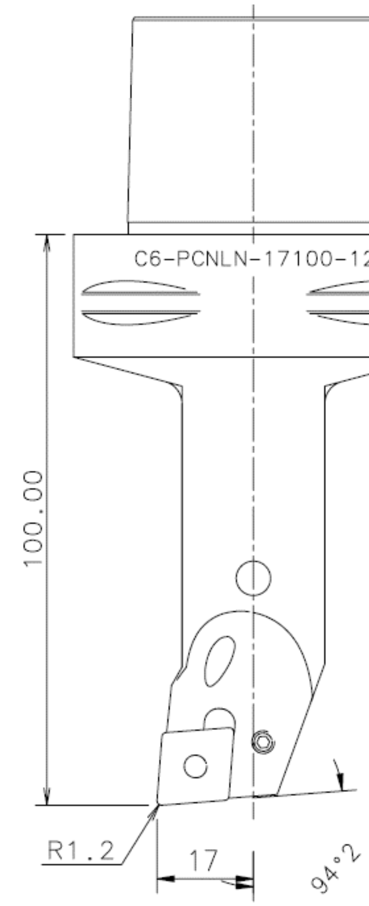


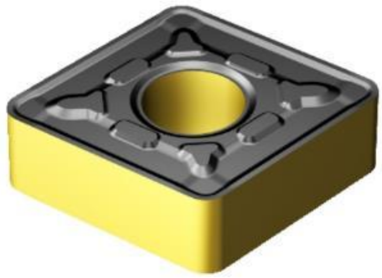
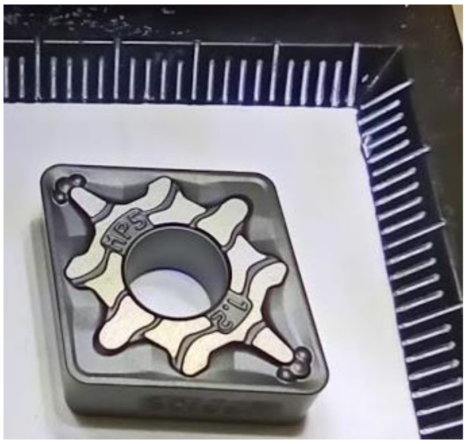
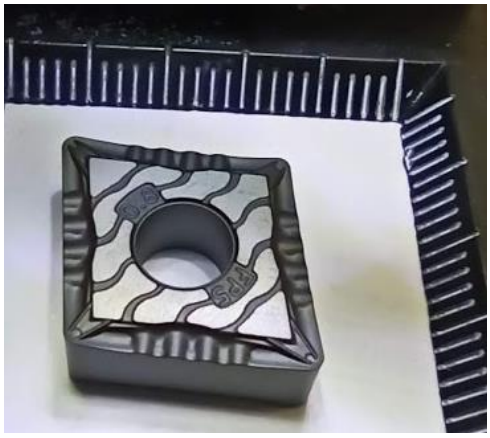
Figure 3.6.1.1 Tool used for boring experimentations.

Two roughing inserts CNMG12 were tested.

One finishing insert of CNMG12 was tested.

The cutting inserts used for experimentations of boring are listed in the table below with a photo of their chip breaker.

Table 3.6.1.1 Chip breakers of turning inserts used for experimentations of boring [78].

Cutting inserts CNMG 12 used for experimentations of boring.			
producer	designation	application	picutre
Sandvik	CNMG 12 04 12-PR 4225	roughing	
Walter	CNMG120412-MP5 WPP10S	roughing	
Walter	CNMG120408-FP5 WPP10S	finishing	

Cutting parameters used during experimentation of boring are listed in the table below.

Table 3.6.1.2 Cutting parameters recommended by producer and cutting parameters used during experimentations.

General information			Application limits				Principle application		Recommended by producer			Values during experimentations							
producer	designation	application	a_p min (mm)	a_p max (mm)	f min (mm)	f max (mm)	v_c min (m/min)	v_c max (m/min)	a_p (mm)	f (mm)	v_c (m/min)	a_p 1 (mm)	a_p 2 (mm)	a_p 3 (mm)	f1 (mm)	f2 (mm)	f3 (mm)	f4 (mm)	vc essais (m/min)
Sandvik	CNMG 12 04 12-PR 4225	roughing	1	7	0.25	0.70	240	380	3.6	0.4	141	2.5	3	3.5	0.35	0.40	0.45	x	140
Walter	CNMG 12 041 2-MP5 WPP10S	roughing	1	5	0.20	0.45	x	x	2.5	0.31	138	2.5	3	3.5	0.35	0.40	0.45	x	140
Walter	CNMG 12 04 08-FP5 WPP10S	finishing	0.20	2	0.08	0.25	x	x	0.41	0.168	163	0.4	0.8	1.2	0.11	0.14	0.17	0.20	140

3.6.2 Experimentations

The workpiece was predrilled. Pre-drilling enabled the boring tool to enter the hole and helped also to eliminate material close to the centre of the workpiece, because it is not possible to obtain constant cutting speed that close to the centre. The closer to the workpiece centre the more the spindle must turn the workpiece to obtain constant cutting speed at every diameter. There is a limiting diameter where the spindle cannot turn any quicker to compensate the smaller diameter (either physical limitation of the spindle or programmed limit). Cutting speed is therefore lower towards the centre of the workpiece. Constant cutting speed was kept during all of experimentation.

As for the experimentation of roughing and finishing, the workpiece with designation 2C was used. The experimentations of boring followed the previous experimentations of roughing and finishing.

Workpiece was further prepared by drilling a hole of diameter 36mm.

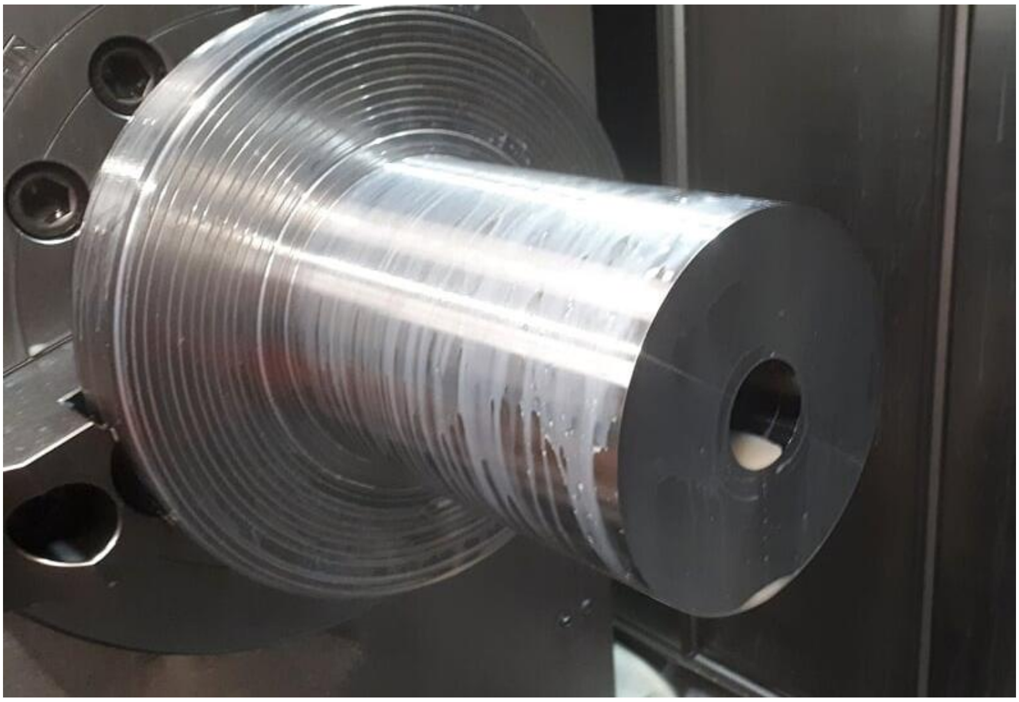


Figure 3.6.2.1 Workpiece before boring, pre-drilled hole in centre.

Figure 3.6.2.2 Workpiece and tool during experimentation of boring.

The diameter was then enlarged by boring. After every use of the tool, chips were sampled and tagged with an identification number.

Workpiece during experimentations of boring is shown in the figure below.

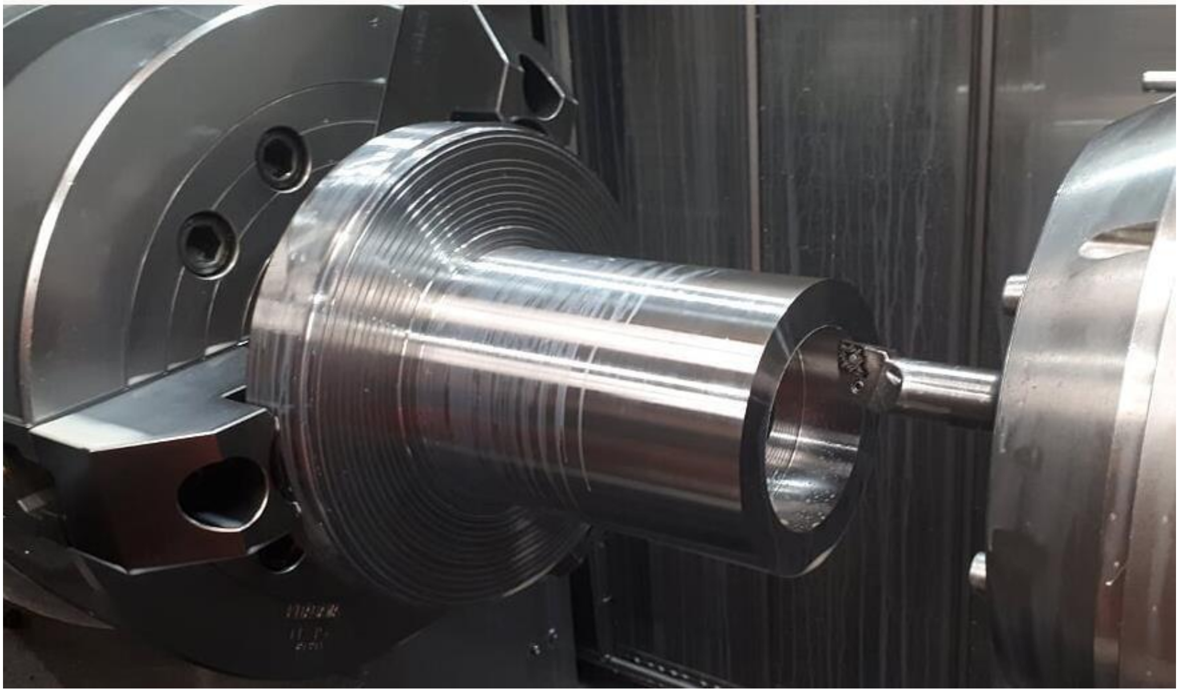


Figure 3.6.2.3 Workpiece during experimentation of boring.

3.6.3 Chip fragmentation during boring

The photos of chip samples were taken while using the same set up as described in chapters concerning experimentation of roughing and finishing, from 15 cm distance.

Photos were also retouched to adjust brightness and contrast, cropped and zoomed to 200%.

Results of the chip fragmentation obtained are shown in the following figures.

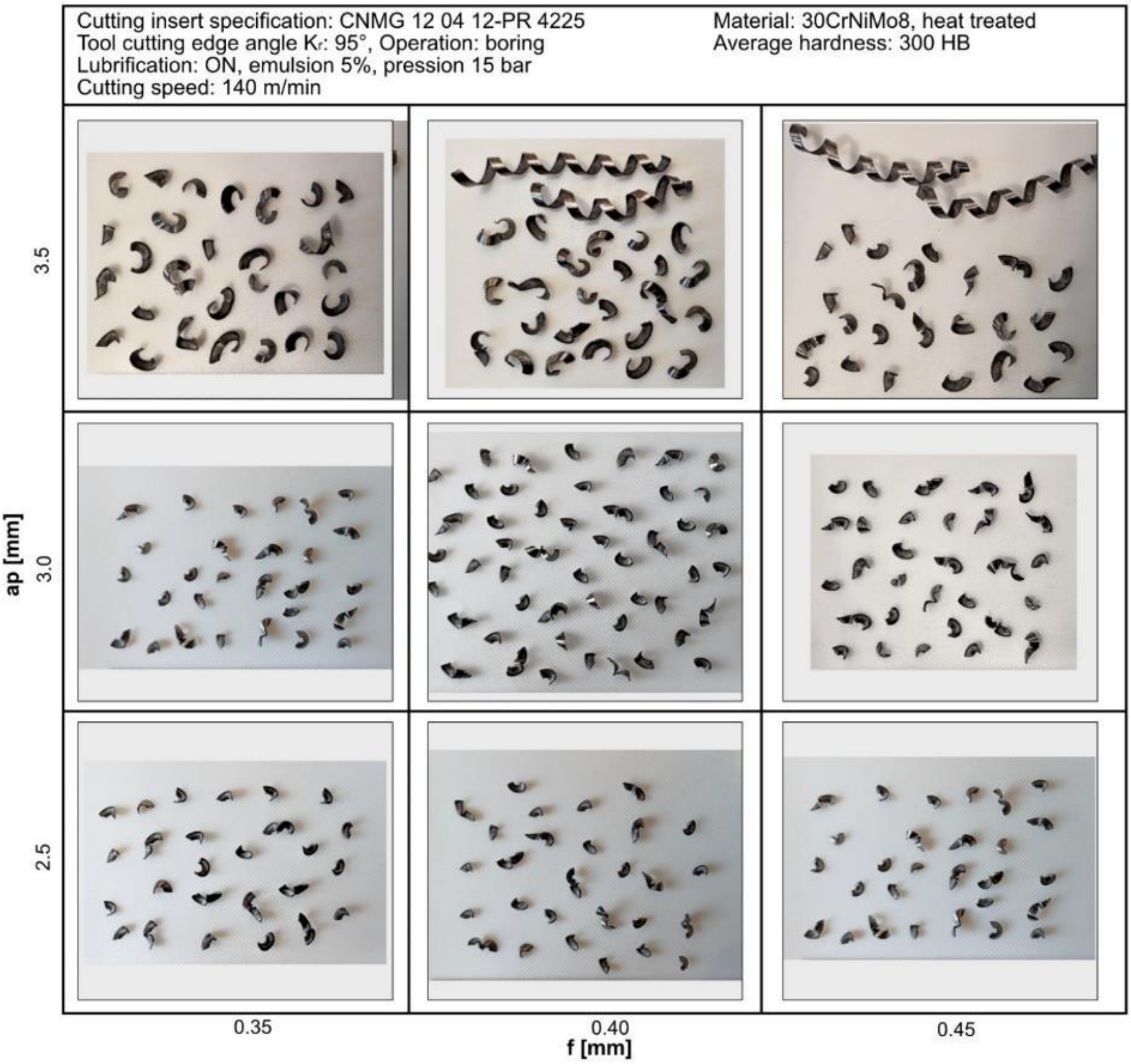


Figure 3.6.3.1 Chip fragmentation for boring roughing with Sandvik indexable cutting insert CNMG 12 04 12-PR 4225.

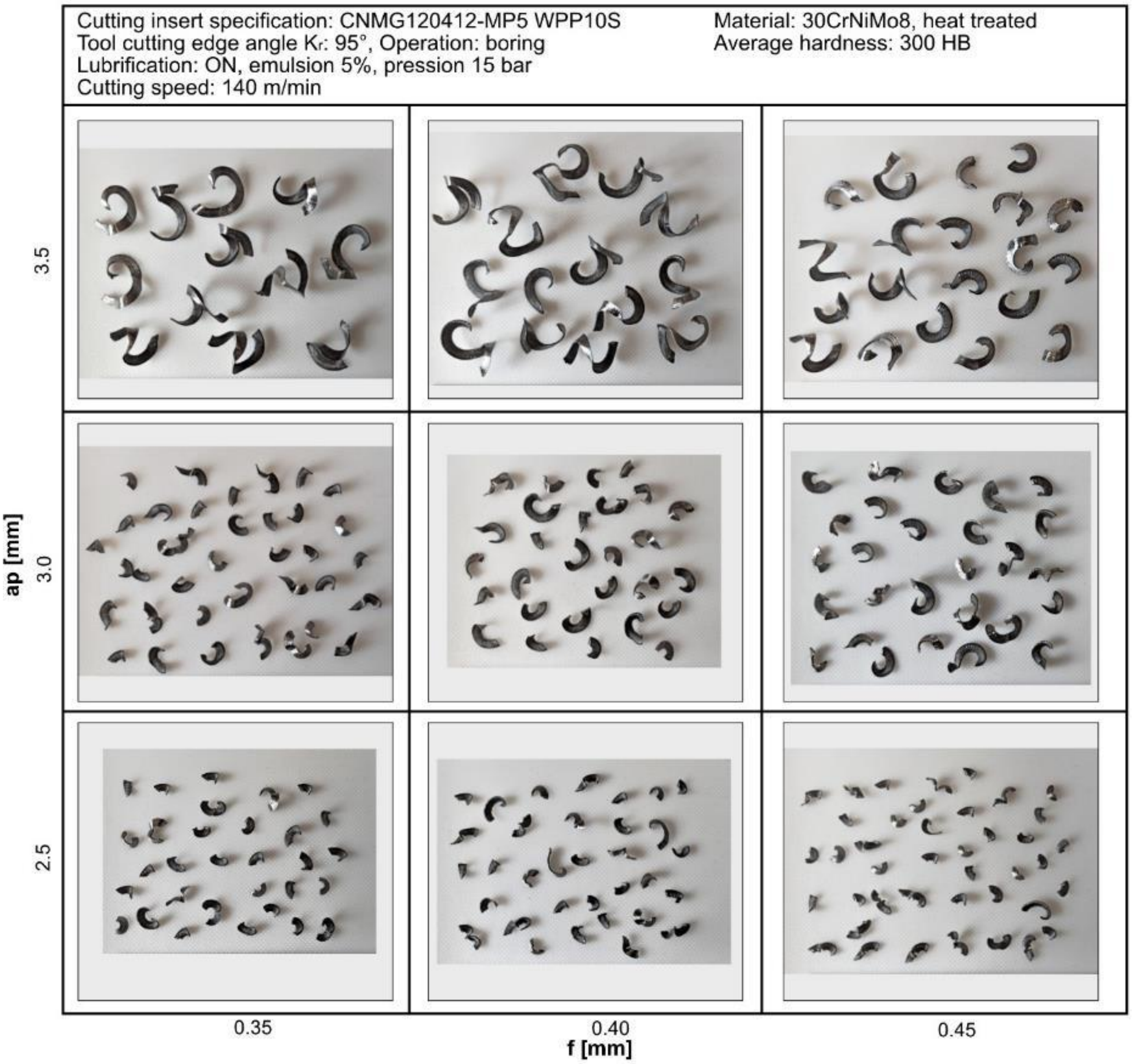


Figure 3.6.3.2 Chip fragmentation for boring roughing with Walter indexable cutting insert CNMG 12 04 12-MP5 WPP10S.

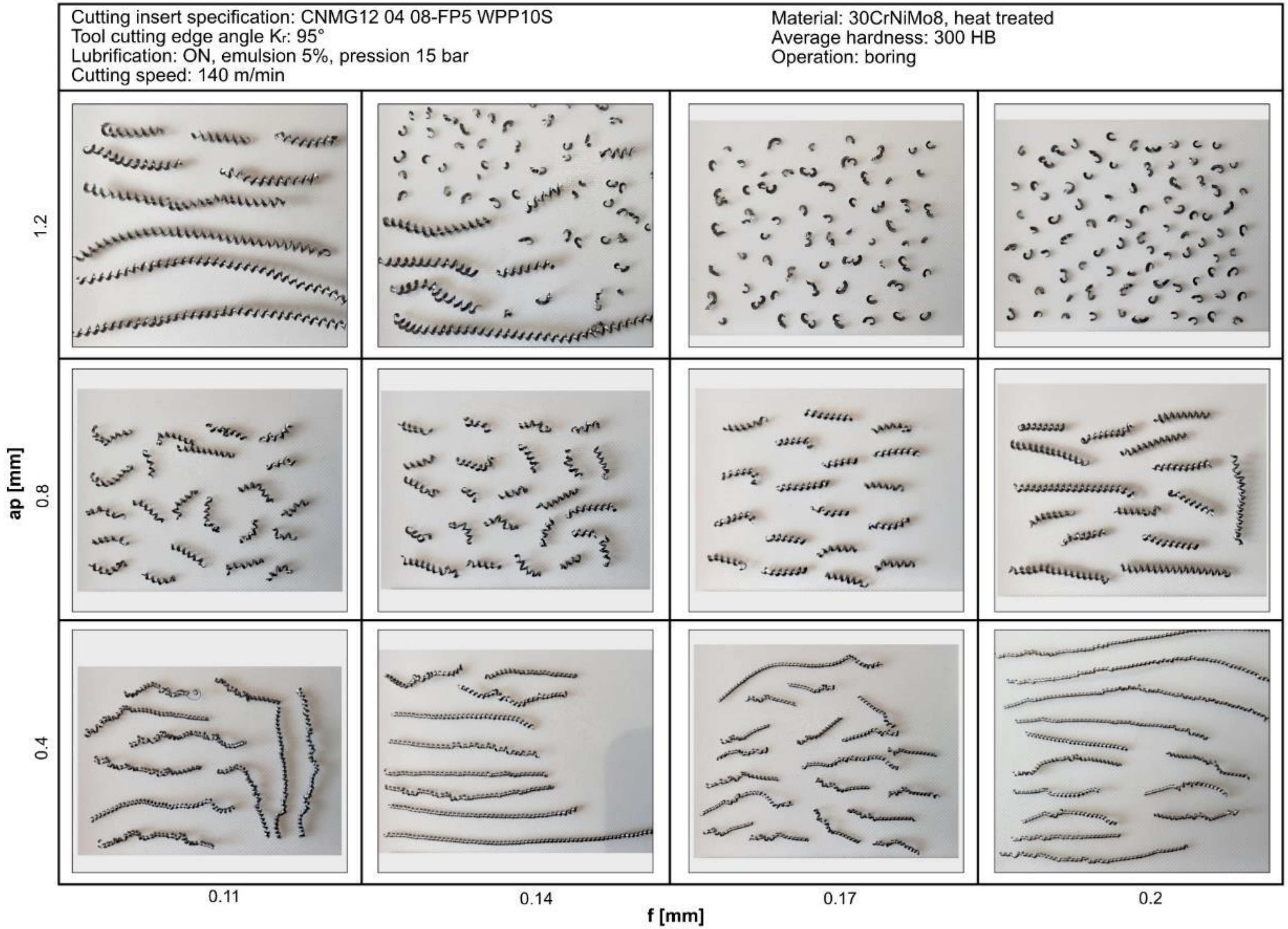


Figure 3.6.3.3 Chip fragmentation for boring finishing with Walter indexable cutting insert CNMG 12 04 08-FP5 WPP10S.

3.6.4 Overall results for boring

Recommendations were determined as following:

For roughing keep the same cutting insert as in original cutting sequence (Sandvik CNMG 12 04 12-PR 4225) and use new cutting conditions:

- a_p = 3 mm,
- f = 0.35 mm,
- v_c = 140 m/min (use as depart value and follow by studying tool life in production with different v_c).

For finishing (if implemented) use cutting tool insert Walter CNMG 12 04 12-FP5 WPP20S

- a_p = 1.2 mm,
- f = 0.17 mm at least,
- v_c = 180 m/min (use as depart value and follow by studying tool life in production with different v_c).

EXPERIMENT 5: INTERNAL THREAD MILLING

Internal threads were in original cutting sequence fabricated by turning and tapping.

During turning of the threads there were significant problems with insufficient chip fragmentation, and vibrations. The turned diameter was quite small for internal turning and the turning tool needed to be quite long, causing vibrations.

During tapping of the threads there were problems with non-fragmented chips that would get stuck around the tapping tool. Using taps also has risk in case of the tool breakage. If the tap breaks in the hole, it can be challenging to manage to extract the broken tool from the hole. While extracting the tool, the thread in the workpiece can be damaged as well. Considering that thread fabrication is one of the last stages of machining of the workpiece, this could mean damaging an expensive workpiece with added value of multiple hours of machining (for bigger head bolts especially.

As a proposed solution to both problems, thread milling was tested.

There were two types of previously turned internal threads:

- M30x3.5-6H,
- M42x4.5-6H.

There were two types of previously tapped internal threads:

- M16x2-6H,
- M20x2.5-6H.

Both types were featured in different lengths. Overall variations are represented in the following table.

Two types of thread milling tools were chosen to be tested to replace original strategies:

- thread milling tool with inserts,
- solid thread milling tool.

Thread M30x3.5-6H was chosen as representative test thread for the thread milling tool with indexable insert.

Thread M16x2-6H was chosen as the test thread of the monobloc tread milling tool.

Both types of threads were tested following the same procedure:

- test tool trajectories were generated in Esprit CAM,
- test tool trajectories were simulated in Esprit CAM,
- test NC programs were generated using a correct post-processor,
- tool put in tool holder,
- tool measured with tool-presetter,
- tool mounted in the automatic tool changer,
- tool diameter corrections were determined,
- tool correctors were entered in the machine,
- tool was called from the ATC,
- the tool was palped with Renishaw HPRA for checking the length of the tool,
- program was called with offset in Z axis for safety reasons (to machine only 1 mm in depth),
- program was called without offset,
- the resulting machined thread was inspected,
- if needed, cutting parameters and /or tool corrections were modified.

Both types of tools were tested on the same workpiece.

Workpiece dedicated to experiments was used for the first thread milling experiment.

The workpiece was prepared by face turning and drilled to be threaded were drilled.

Figure -.1 Workpiece for thread milling experiment prepared, face turned, drilled holes.

Tool measurement in the tool-presetter is displayed on the figure below.

Figure 3.6.4.2 Tool pre-setter display while measuring of solid thread milling tool.

For verification of the machined threads, equipment available in the workshop was used. Thread gauges that are used in production to verify the threads were used during the experimentations.

Figure 3.6.4.3 Thread gauges used for machined thread verification.

3.6.5 Thread milling tool with inserts

Thread milling tools with indexable inserts was chosen for the larger diameters of thread: M30 and M42. Because the threads have different pitches, different tools must be used.

Figure 3.6.5.1 Thread milling tool with cutting inserts.

Parameters of the tool are shown in the figure below.

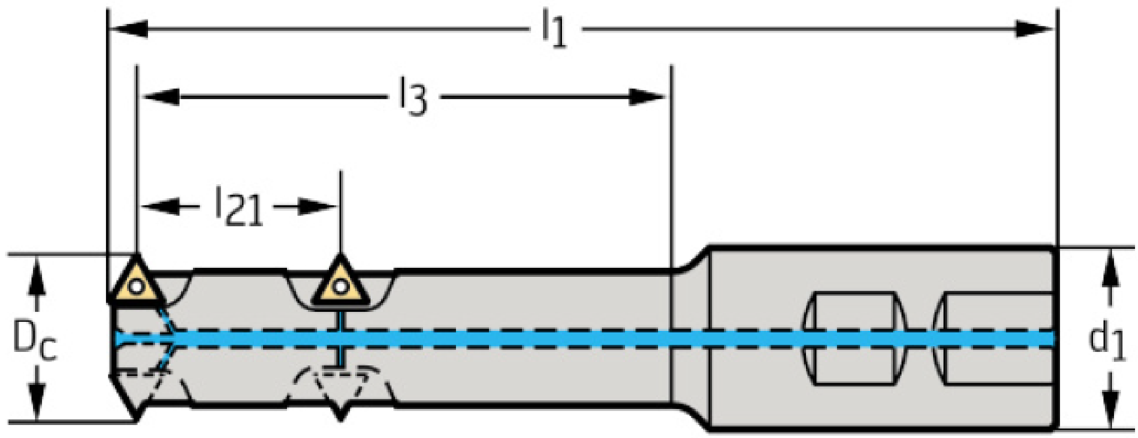


Figure 3.6.5.2 Parameters of Walter Tools thread milling tool with cutting inserts [79].

Parameters of the thread milling tool with cutting inserts are listed in the table below.

Table 3.6.5.1 Parameters of thread milling cutting tool T2711-24-W25-3-09-2-31.5 [79].

Tool designation	Maximum pitch	Cutting edge diameter	Driver size	Usable length	Row distance	Overall length	N. of inserts
-	P_{max}	D_c (mm)	d_1 (mm)	l_3 (mm)	l_{21} (mm)	l_1 (mm)	x
T2711-24-W25-3-09-2-31.5 with P26300-0902-D67 WSM37S	3.5	24	25	42	58	131	6

Correction of tool radius for M30x3.5 can be found in the following figure. For M30x3.5 the corection reads -0,22 mm.

Metric thread in accordance with DIN 13

Thread nominal diameter D_N	P	r	Radius correction: Minimum dimension for H tolerances	Radius correction: Middle of the tolerance range for a 6H tolerance	Radius correction: Middle of the tolerance range for a 6G tolerance
[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
≥ 24	1,5	0,1	-0,05	-0,10	-0,12
	2	0,1	-0,10	-0,15	-0,17
	3	0,2	-0,10	-0,16	-0,19
	3,5	0,2	-0,15	-0,22	-0,24
	4	0,2	-0,20	-0,27	-0,30
	4,5	0,2	-0,25	-0,33	-0,36
	5*	0,2	-0,30	-0,38	-0,42
		0,4	-0,10	-0,18	-0,22
	5,5	0,4	-0,15	-0,24	-0,27
	6	0,4	-0,20	-0,29	-0,33
	8	0,4	-0,40	-0,51	-0,56
	10	0,4	-0,59	-0,71	–

Based on the pitch diameter tolerances in accordance with DIN ISO 965-1. Valid from M24.
* Important: For P = 5 mm, we recommend an insert radius r = 0.2 mm. Please take this into account when selecting the radius correction values.

Figure 3.6.5.3 Tool correction for thread milling cutters T2711 / T2712 / T2713 by Water Tools [52].

3.6.5.1 **M30x3.5-6H**

The thread milling tool with cutting inserts for pitch od 3.5 mm was tested on machining of metric thread M30. Thread milling tool is limited by the pitch but can be used on multiple diameters.

Cutting conditions used were:

- a_e = 1.75 mm,
- a_p = 7 mm,
- numbre of passes in direction AE NOPae = 1,
- numbre of passes in direction AP NOPap = 10,
- v_c = 176 m/min,
- N = 2330 1/min,
- f_z = 0,241 mm,
- feed at circumference v_{fe} = 1690 mm/min,
- feed at centre of the tool v_f = 338 mm/min,
- Pc = 0,887 kW (value estimated by tool producer),
- C_c = 3,63 Nm (value estimated by tool producer),
- T = 150 min (value estimated by tool producer).

There is a burr because there was not machined the usual chamfer at the hole before milling the thread.

The machined surface was excellent, without presence of facets.

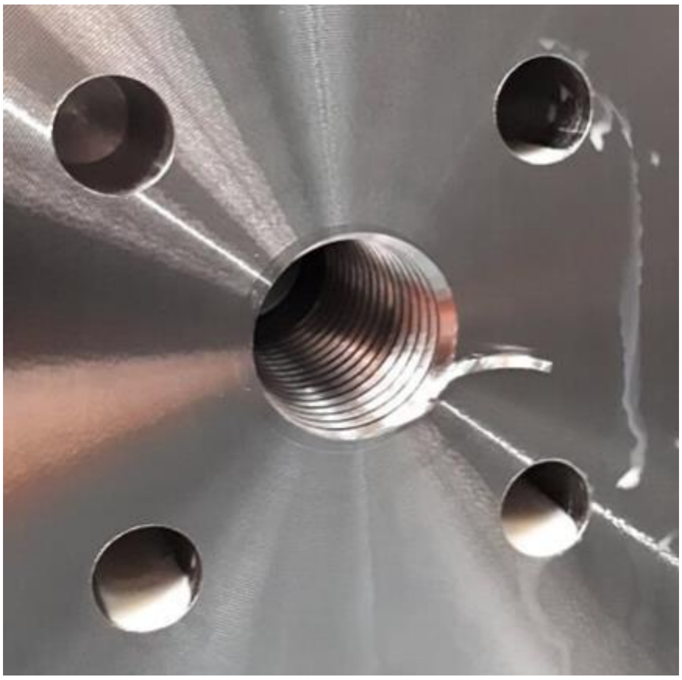


Figure 3.6.5.4 Central thread machined using thread milling tool with cutting inserts.

The thread had correct dimension after first try. The machined surface was clear of signs of vibrations (facets) unlike the turned thread in the original cutting sequence.

Thread gauge in the hole is illustrated in the figure below.

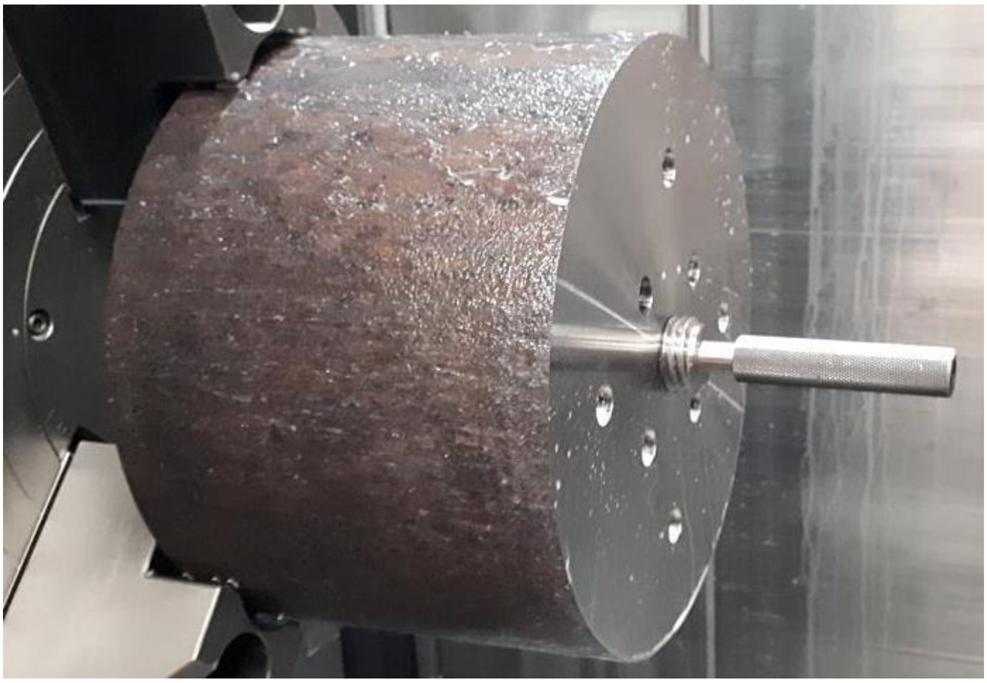


Figure 3.6.5.5 Thread gauge inserted in the machined threaded hole.

The cycle time for operation of thread milling of thread M30x3.5 was simulated at $T_{simulation}$ = 37 s and measured at real cycle time T_{real} = 38s.

The machining was later repeatedly tested in production with consistent results.

3.6.5.2 **Solid thread milling tool**

Solid carbide tools were used for thread milling of smaller diameters.

Solid thread milling tool was chosen for the smaller diameters – M16 and M20.

Solid thread milling tool was experimentally tested on metric thread M16 on two tool lengths.

The two chosen cutting tools vary only in length. Longer tool results in risk of vibrations.

The chosen solid thread milling tools have multiple ranges of cutting edges. Compared to classical thread milling tools with only one range of teeth the machining time is shorter even though the cycle time is usually longer compared to that of a tap.

Parameters of the tool are represented in the following figure:

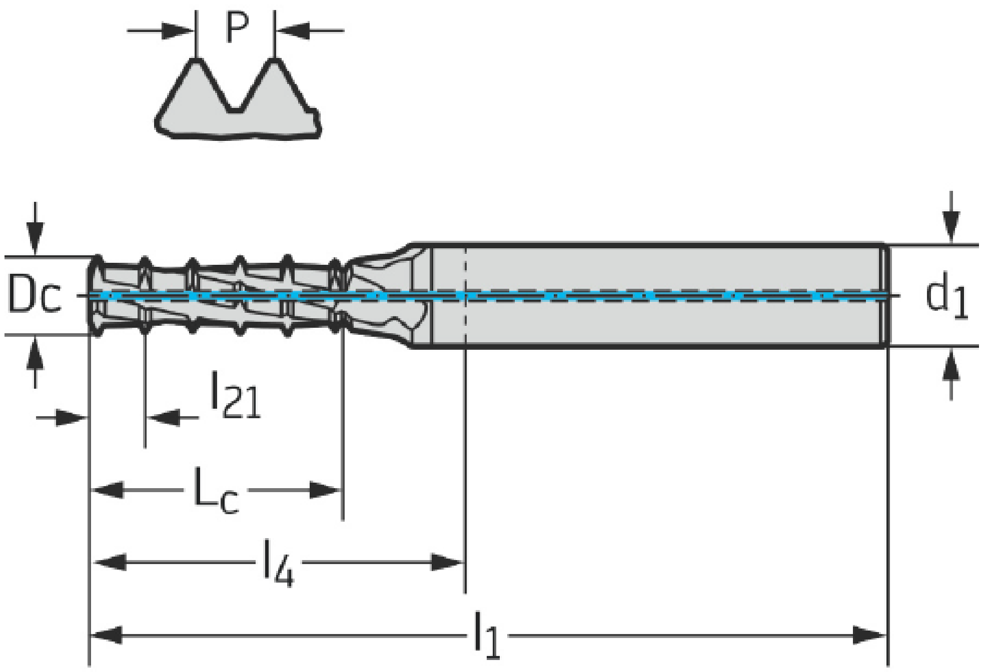


Figure 3.6.5.6 Parameters of solid thread milling cutter by Walter Tools [80].

Parameters of this cutting tool are listed in the table below.

Table 3.6.5.2 Parameters of used solid thread milling cutters.

Tool designation	Cutting edge diameter	Driver size	Max. depth of cut	Maximum overhang	Overall length	N. of flutes	Programming radius (unique)
-	D_c (mm)	d_1 (mm)	L_c (mm)	l_4 (mm)	l_1 (mm)	Z	Rprg (mm)
TC620-M16-A1E-WB10TJ	13.1	16	42	58	106	5	6.543
TC620-M16-A1D-WB10TJ	13.1	16	32	58	106	5	6.43

Real tool radius called programming radius Rprg varies slightly from the theoretical value of tool radius (D_c/2). Value of programmed radius Rprg is given by tool producer and was verified by a tool pre-setter. With tool wear, the radius of the tool decreases. Tool producer is able to retouch this radius multiple times to return the radius to its original value, this increases tool life by at least two times.

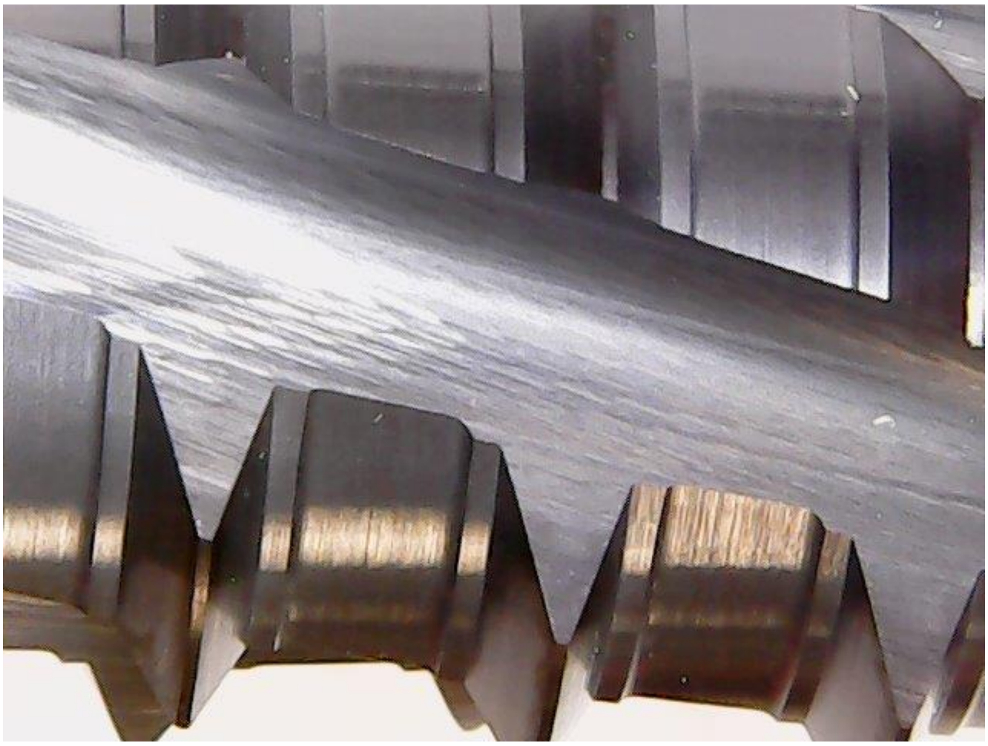


Figure 3.6.5.7 Cutting edges of solid thread milling tool TC620-M16-A1D-WB10TJ up-close.

Interferences of the machined surface and theoretical normalized surface were calculated using algorithm described in the theoretical analysis. The correction was estimated for both tools.

Correction of the tool diameter were given by the tool producer. As both the short version and long version of the tool had the same pitch and diameter, the vale of correction was the same.

Corrections of tool radius given by tool producer are shown in the figure below.

Metric thread in accordance with DIN 13

Thread nominal diameter D_N	P	Radius correction		
		Minimum dimension for H tolerances	Middle of the tolerance range for a 6H tolerance	Middle of the tolerance range for a 6G tolerance
[mm]	[mm]		[mm]	[mm]
≥ 3 and ≤ 22	0,50	Rprg.	-0,025	-0,035
	0,70	Rprg.	-0,030	-0,041
	0,80	Rprg.	-0,031	-0,043
	1,00	Rprg.	-0,038	-0,051
	1,25	Rprg.	-0,040	-0,054
	1,50	Rprg.	-0,045	-0,061
	1,75	Rprg.	-0,050	-0,067
	2,00	Rprg.	-0,053	-0,072
	2,50	Rprg.	-0,056	-0,077

Based on the pitch diameter tolerances in accordance with DIN ISO 965-1.

Figure 3.6.5.8 Radius corrections for solid carbide thread milling cutters TC620 and TC685 by defined by Walter Tools [52].

For M16x2, the radius correction is R Rprg – 0,053 mm.

3.6.5.3 **M16x2-6H machining – longer tool**

Longer version of the solid milling tool – TC620-M16-A1E-WB10TJ was tested on a workpiece dedicated purely for experimentation.

Real tool diameter was measured by the tool producer as: Rprg = 6.543mm. This value was engraved on the tool.

Radius correction for middle of tolerance class 6H determined by tool producer as:

correction = -0.053mm.

Tool radius entered in the CNC machine was therefore:

$R_{compensated}$ = Rprg – correction = 6.543-0.053 = 6.49 mm.

- a_e = 1.0 mm,
- a_p = 12 mm,
- numbre of passes in direction AE NOPae = 1,
- numbre of passes in direction AP NOPap = 4,
- v_c = 87.2 m/min,
- N = 2120 1/min,
- f_z = 0,145 mm,
- feed at circumference v_{fe} = 1540 mm/min,
- feed at centre of the tool v_f = 278 mm/min,
- P_c = 0,886 kW (value estimated by tool producer),
- C_c = 3,99 Nm (value estimated by tool producer),
- T = 160 min (value estimated by tool producer).

Figure 3.6.5.9 Tool TC620-M16-A1E-WB10TJ in toolholder.

Tool before machining of a thread is displayed in the figure below.

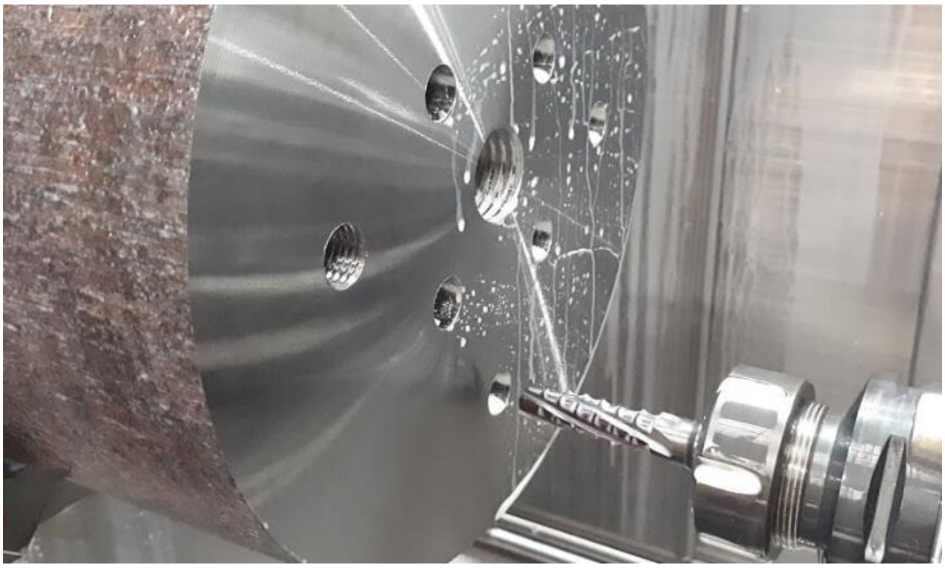


Figure 3.6.5.10 Workpiece and thread milling solid tool before machining of a thread.

8 holes were prepared for machining. Cutting conditions were changed between the holes as ideal cutting conditions were searched.

Presence of vibration during machining was noted using default cutting parameters. Typical vibrations sounds were heard during the machining and typical facets were presented on the machines surface.

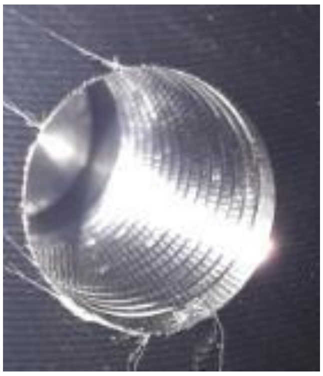


Figure 3.6.5.11 Facets on the machines surface of the thread caused by vibrations.

Different cutting parameters were tested to try to empirically eliminate the vibrations.

The cutting was divided into roughing and finishing to decrease a_p and cutting speed was increased to v_c = 110 m/min, both in attempt to eliminate vibrations. The facets were less present using the new cutting conditions.

6 out of 8 holes threaded, then the tool was broken due to machine error – blocked spindle was reset and therefore was de-blocked enabling rotation of the workpiece.

Figure 3.6.5.12 Workpiece with labels of threaded holes.

3.6.5.4 **M16x2-6H machining – shorter tool**

Shorter version of the solid milling tool – TC620-M16-A1D-WB10TJ was tested on a production workpiece HP300.

Real tool diameter was measured by the tool producer as: Rprg = 6.43mm. This value was engraved on the tool

Radius correction for middle of tolerance class 6H determined by tool producer as:

correction = -0.053mm. Because the longer and shorter tool had same pitch and diameter, the value of correction defined by tool fabricant was the same.

Tool radius entered in the CNC machine was therefore:

$R_{compensated}$ = Rprg – correction = 6.43 - 0.053 = 6.377 mm.

Cutting conditions used were:

- ae = 1.0 mm,
- ap = 10 mm,
- numbre of passes in direction AE NOPae = 1,
- numbre of passes in direction AP NOPap = 4,
- v_c = 88 m/min,
- N = 2140 1/min,
- f_z = 0,145 mm,
- feed at circumference v_{fe} = 1550 mm/min,
- feed at centre of the tool v_f = 281 mm/min,
- P_c = 0,745 kW (value estimated by tool producer),
- C_c = 3,33 Nm (value estimated by tool producer),
- T = 160 min (value estimated by tool producer).

Figure 3.6.5.13

Value of tool radius measured by tool fabricant engraved on the tool is displayed in the figure below.

Figure 3.6.5.14

Presence of vibration during machining was noted using default cutting parameters. Vibrations were heard and facets were present on the machined surface as well.

Different cutting parameters were tested to try to empirically eliminate the vibrations. Even when increasing cutting speed slightly and machining in 2 passes (roughing and finishing), the vibrations were still present.

3.6.6 Overall results of internal thread milling strategy

Both solid thread milling tool and thread milling tool with cutting inserts produced fragmented chips that were easily evacuated by the cutting fluid and were not possible to take sample of. The excellent chip fragmentation and evacuation was the main goal of employing this strategy of thread machining. In the original cutting sequence either tapping nor internal thread turning produced acceptable chips and the chips had to be removed by the operator.

Employing thread milling strategy would result in slightly longer machining time but gain in autonomy thanks to great chip evacuation.

3.6.6.1 Overall results for thread milling tool with cutting inserts

The machined thread had acceptable dimension and machined surface on the first try.

Improved typology of chips was the main objective of this new machining strategy. Chips produced during experimentation of thread milling with tool with cutting inserts were acceptable, fragmented and well evacuated. The produced acceptable chips represented a huge improvement compared to the internal thread turning in the original cutting sequence. After internal thread turning, chips were long and needed to be manually taken out of the central hole with pincers.

Machining time of M30x3.5 of depth 50.5 mm

- $T_{M30,original}$ = **31 sec** (thread turning),
- $T_{M30,new}$ = **37 sec** (thread milling).

3.6.6.2 Overall result for solid thread milling tools

For both version of the thread milling tool, vibrations were present during machining.

Even passing to two step strategy of roughing and then finishing (therefore decreasing the value of depth of cut) and increasing of cutting speed did not eliminate the problem with vibrations. Even the shorter version of the tool presented with vibrations.

Machining time of M16x2 of depth 35 mm:

- $T_{M16,original}$ = **21 sec** (thread tapping),
- $T_{M16,new}$ = **35 sec** (thread milling).

Simulation time of 4 threaded holes M20x3.5 was:

- $T_{M20,original,\ simulation}$ = **21 sec** (thread tapping),
- $T_{M20,new,\ simulation}$ = **35 sec** (thread milling).
-

3.7 EXPERIMENT 6: EXTERNAL THREAD TURNING

During external thread turning, long unfragmented chips that blocked the chip conveyor were observed. To try obtaining more acceptable type of chips, different penetration modes during turning of the thread were tried. In the original cutting sequence radial penetration mode was used and it produced long, unfragmented chips that blocked the chip conveyer every time.

Different was tested to obtain chips that would be acceptable for automation cycle of machining without the need to cut the chips manually.

3.7.1 Programming

In the original cutting sequence, a classic radial penetration mode was used to machine the external thread. Flank infeed was tried because it generally results in better chip control.

The different methods of penetration during external thread turning were programmed in Eprit CAM. Choices for penetration modes during turning in Esprit CAM are listed in the following figure.

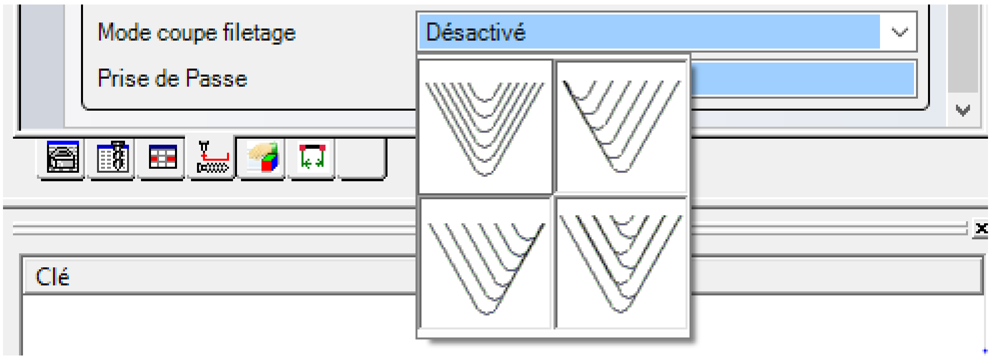


Figure 3.7.1.1 Choices of penetration mode during external turning in Esprit CAM

On following two figures, the difference between radial infeed and modified flank infeed can be remarked.

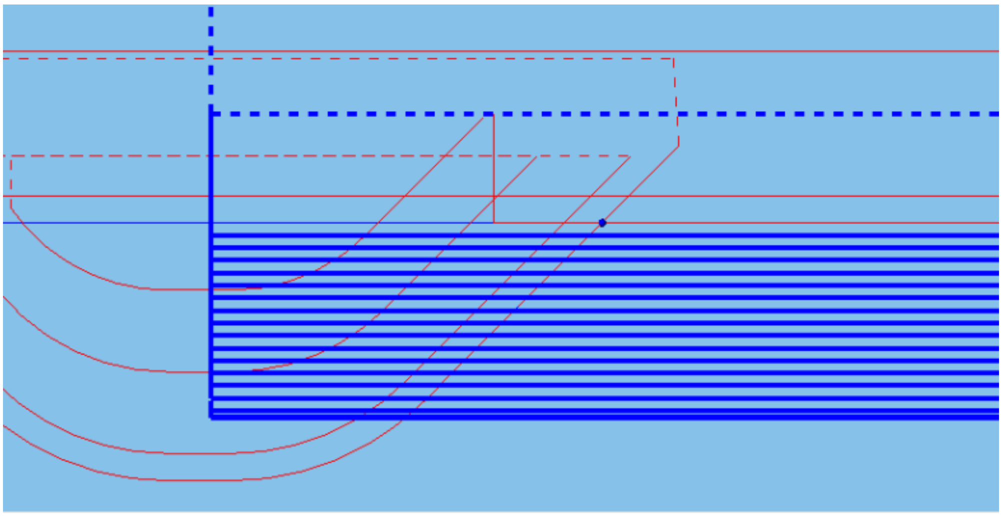


Figure 3.7.1.2 Tool trajectories in Esprit CAM for radial flank infeed penetration method (from the right side) during external thread turning.

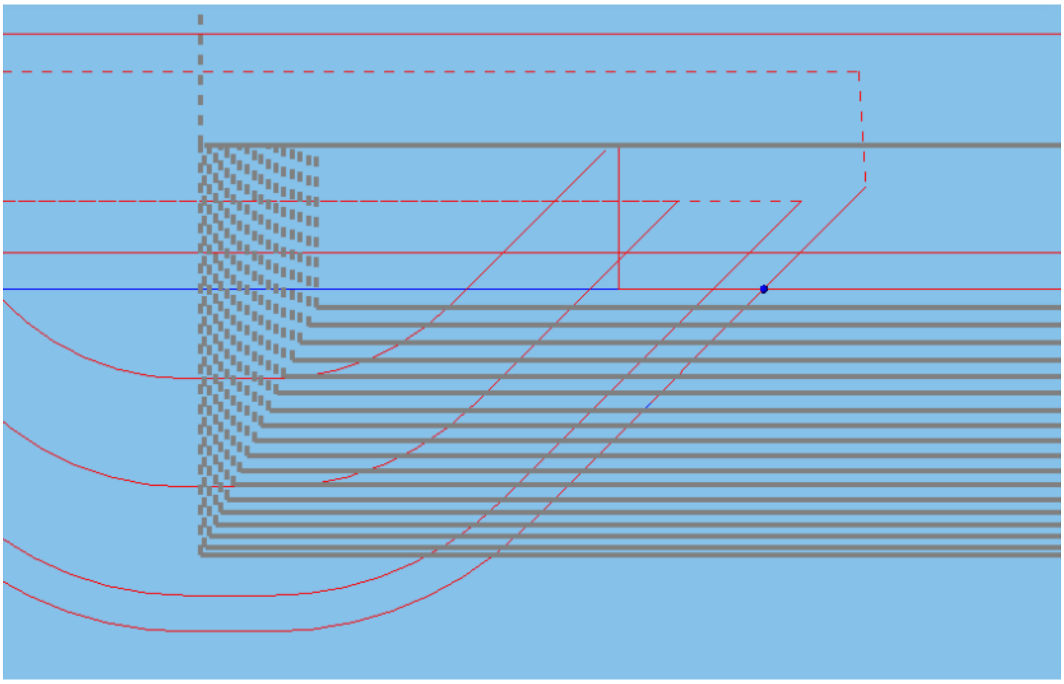


Figure 3.7.1.3 Tool trajectories in Esprit CAM for modified flank infeed penetration method during external thread turning.

3.7.2 Experimentations on external thread turning

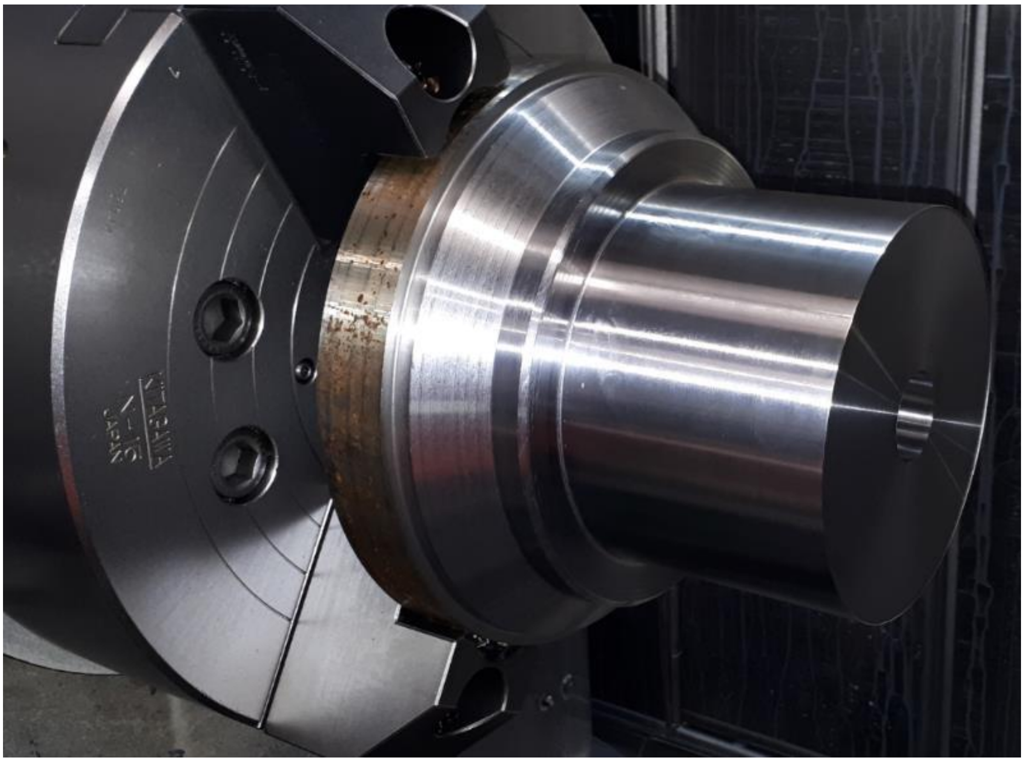


Figure 3.7.2.1 Workpiece before machining of external thread.

Chips obtained during external thread turning of the locking bolt thread are

Figure 3.7.2.2 Chips after machining the external thread with radial penetration mode for locking bolt HP3 (M140x6) in original cutting sequence.

Figure 3.7.2.3 Workpiece and chips in chip conveyor after external thread turning with flank infeed.

An incremental infeed mode was also tested as well but without an improvement in chip typology.

3.7.3 Overall results of external thread turning

It was determined experimentally that modified flank infeed is the best for large external threads of locking bolts was the most adapted for chip typology. Modified flank infeed resulted in chips long but fragmented and the chips were easily evacuated by the chip conveyor.

3.8 EXPERIMENT 7: TROCHOIDAL MILLING – POCKET MILLING

Trochoidal milling was explained in the theoretical analysis. It was chosen as a strategy for pocket milling to replace contouring as it would bring an optimisation of machining time and of cutting forces (axial instead of radial).

3.8.1 Tools and cutting parameters

Two milling tools by producer Walter Tools were tested for trochoidal milling.

Two lengths of tools were chosen. Most of pockets were had depth of 30 mm and only a few models 42 mm. It is always beneficial to have shorter tool if possible because it lowers the tendency to vibrate. It would be possible to have only one tool to machine both types of pockets, but it would limit the cutting parameters. When choosing two lengths of tools, the shallower pockets can be machined quicker with less risk of vibrating. Using two lengths of tools brings risk of human error that the two tools might be interchanged.

The tools used are:

- MC122-16.0W5L-WJ30TF,
- MC122-16.0W4B-WJ30TF.

The difference between these two tools is number of flutes and the length of the tool.

The shorter version was used in the version with 4 flutes to test the difference in chip evacuation.

Both tools can be represented by the following figure, but vary in length and number of flutes.

Figure 3.8.1.1 Representative MC122-16.0W5L-WJ30TF [81].

Their different dimensions are listed in the table below with an explicative figure [81, 82].:

Table 3.8.1.1 Dimension of [81, 82].

Tool designation	Cutting edge diameter	Driver size	Max. depth of cut	Maximum overhang	Overall length	N. of flutes
-	D_c (mm)	d_1 (mm)	L_c (mm)	l_4 (mm)	l_1 (mm)	Z
MC122-16.0W5L-WJ30TF	16	16	50	67	115	5
MC122-16.0W4B-WJ30TF	16	16	32	44	92	4

The dimensions of the tools are represented in the following figure.

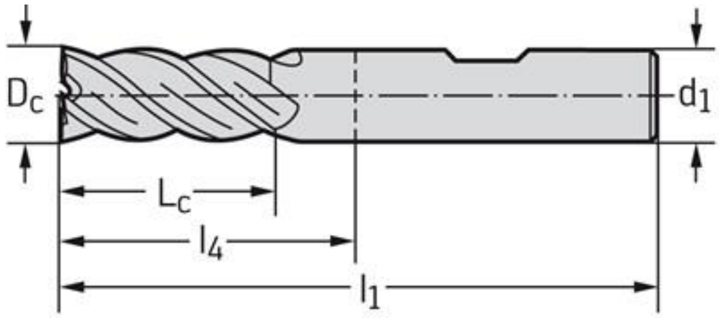


Figure 3.8.1.2 Explicative figure for symbols indicating tool specifications [81].

The cutting parameters used were typical or trochoidal milling as a type of high efficiency milling, in sense that axial depth a_p was much more important than the radial depth of cut a_e. The axial depth of cut was in this case the whole depth of the pocket.

Trochoidal pocket milling was tested with listed cutting parameters.

Table 3.8.1.2 Cutting parameters used for trochoidal milling experimentation.

trochoidal milling	General information					Cutting parameters - Roughing				Cutting parameters - Finishing			
application	producer	designation	D (mm)	l_c (mm)	Z	a_p (mm)	a_e (mm)	f_z (mm)	v_c (m/min)	a_p (mm)	a_e (mm)	f_z (mm)	v_c (m/min)
pocket HP3, 2 grooves	Walter	MC122-16.0W5L-WJ30TF	16	50	5	30	1.6	0.168	152	30	0.32	0.131	219
pocket HP6, 4 grooves						42	1.6	0.168	152	42	0.32	0.131	219
pocket HP3, 2 grooves	Walter	MC122-16.0W4B-WJ30TF	16	32	4	30	1.54	0.171	152	30	0.32	0.131	219

3.8.2 Experimentations

Trochoidal trajectories of the tool generated in Esprit CAM can be seen on the following picture.

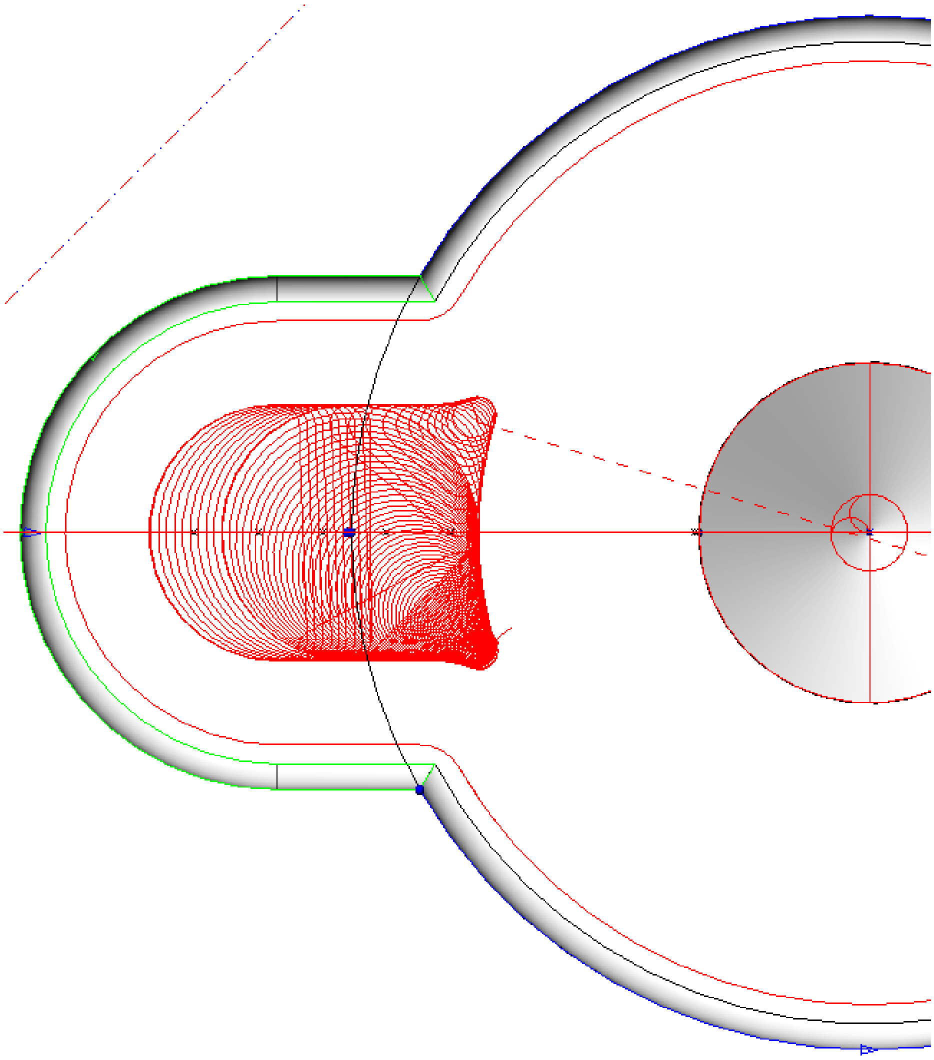


Figure 3.8.2.1 Trochoidal trajectory of the milling tool Esprit CAM.

The workpiece was prepared by external turning, face turning and drilling and turning of a circular pocket:

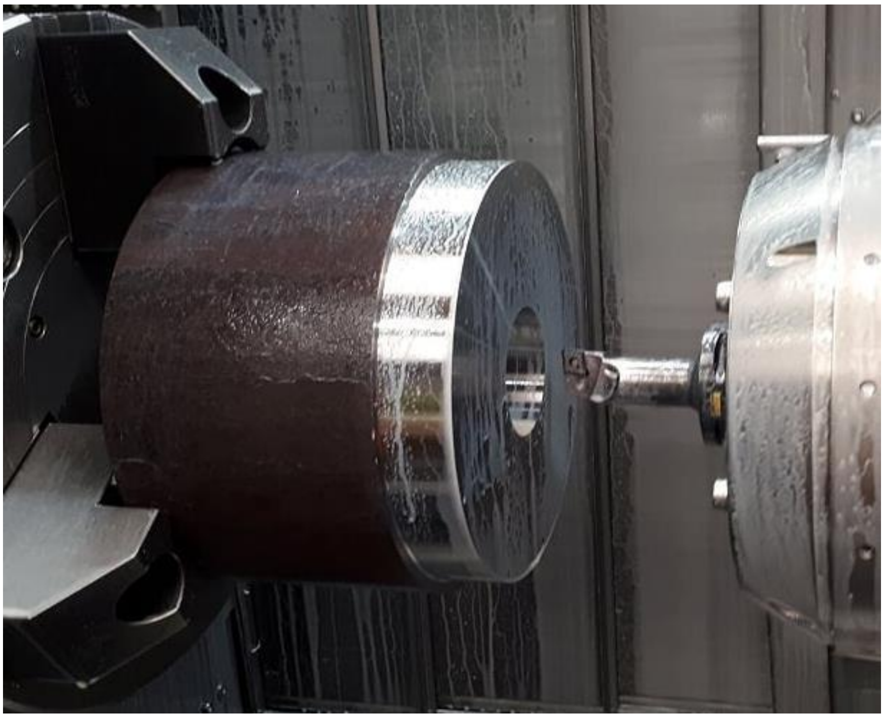


Figure 3.8.2.2 Workpiece prepared for trochoidal milling experimentations, turned and pre-drilled

Tool set up of new milling tools was performed on the Trimos Optima tool setter.

Figure 3.8.2.3 Tool set up using Trimos Optima tool pre-setter.

The tool mounted on a Weldon tool holder with results measured by the Trimos Optima tool pre-setter is displayed in the figure below.

Figure 3.8.2.4 Milling tool MC122-16.0W5L-WJ30TF in toolholder and measured length and diameter by a tool-presetter.

Before testing the tool in all of depth, for safety test the tool used for 1 mm depth to verify the correct tool trajectory as can be seen in the figure below.

Figure 3.8.2.5 Safety test with offset in Z axis, depth of 1mm machined only.

Only then the full depth of the pocket was machined.

Chip fragmentation was sufficient, chips were in form of needles, as was expected. Problem with chip evacuation was observed for the tool with 5 flutes.

Figure 3.8.2.6 Pocket after trochoidal milling, illustration of chip evacuation problem.

A milling tool with lubrifications directed to the flank should solve problem with the evacuation of chips.

The typology and dimension of obtained chips can be noted on following figures. Chips resulting of trochoidal pocket milling of depth 30 mm are captured in the figure below.

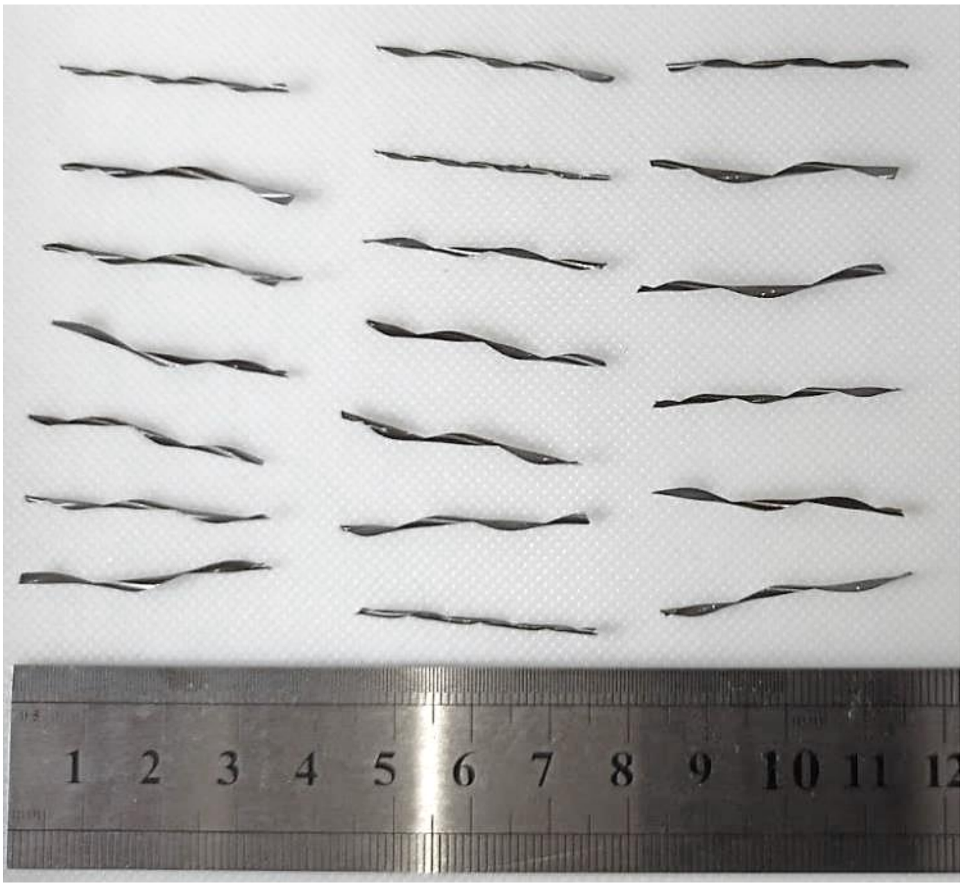


Figure 3.8.2.7 Chips from trochoidal pocket milling of 30 mm depth.

Chips produced during machining of the pocket with depth of 42 mm are shown in the following figure.

Figure 3.8.2.8 Chips from trochoidal pocket milling of 42 mm depth.

Chips were fragmented and needle shaped. The length of the chips corresponded to the axial depth of cut. If shorter chips are demanded, milling tools with chip breakers exist. There are milling tools with chip breakers that would produce chips of the same nature but shorter. Their price is higher though.

Surface after trochoidal milling has marks visible on the wall of the pocket, but they are functionally acceptable.

Figure 3.8.2.9 Vertical marks on the pocket wall after the trochoidal milling

3.8.3 Overall results of trochoidal milling strategy application

In the original cutting sequence the pocket milling using the contouring strategy for locking bolt HP3, the pocket of depth 30 mm was machined by 15 passes of 2 mm and the total machining time of this operation was T = 4 min 53 s (for 2 slots).

In the new cutting sequence, the same pocket was machined using trochoidal milling strategy that had total machining time T = 58 s (for 2 slots). new machining time is 81% quicker than the original one.

For locking bolts that have 4 slots, the saved time would be even more significant.

For HP6, the slot is deeper. The longer version of the tool must be used therefore the cutting parameters are a bit the original machining time was T = 12 min 28 s (for 4 slots). and the new machining time T = 4 min 31 s (for 4 slots). The new machining time is about 64% quicker.

The milling tool with 4 flutes resulted in much better chip evacuation but imposed lower cutting parameters (therefore the machining time was longer) and the tool had tendency to vibrate a bit more than the version with 5 flutes.

For future implementation in production, a tool with flank lubrification for good chip evacuation and rayon 2 mm at the tip is recommended. Radius 2 mm is demanded et the bottom of the pocket.

3.9 ADDITIONAL EXPERIMENTATIONS

Other additional experiments were conducted as possible ways to optimise the machining strategies, but they were not as detailed as previous experimentations.

Groove machining and chip peck cycles were briefly tested in order to judge the suitability of their possible implementation in the cutting sequence.

3.9.1 Groove machining

The groove was originally machined with by contouring with the VNMG cutting insert as finishing of external. To test another type of tool to machine this surface a grooving insert was tested. It was an insert already used in the workshop

A decision to stay with the VNMG geometry was taken but the other possibility was tested to analyse the nature of chips and the surface roughness.

The insert tested was grooving insert N123K2-0600-004-GM.

Cutting parameters:

- f = 0.2 mm,
- v_c = 140 m/min.

Figure 3.9.1.1 Grooving insert and roughing of the groove.

Better chip evacuation was observed compared to turning in the original cutting sequence, but chips were still unfragmented and quite long. Some chips were fragmented

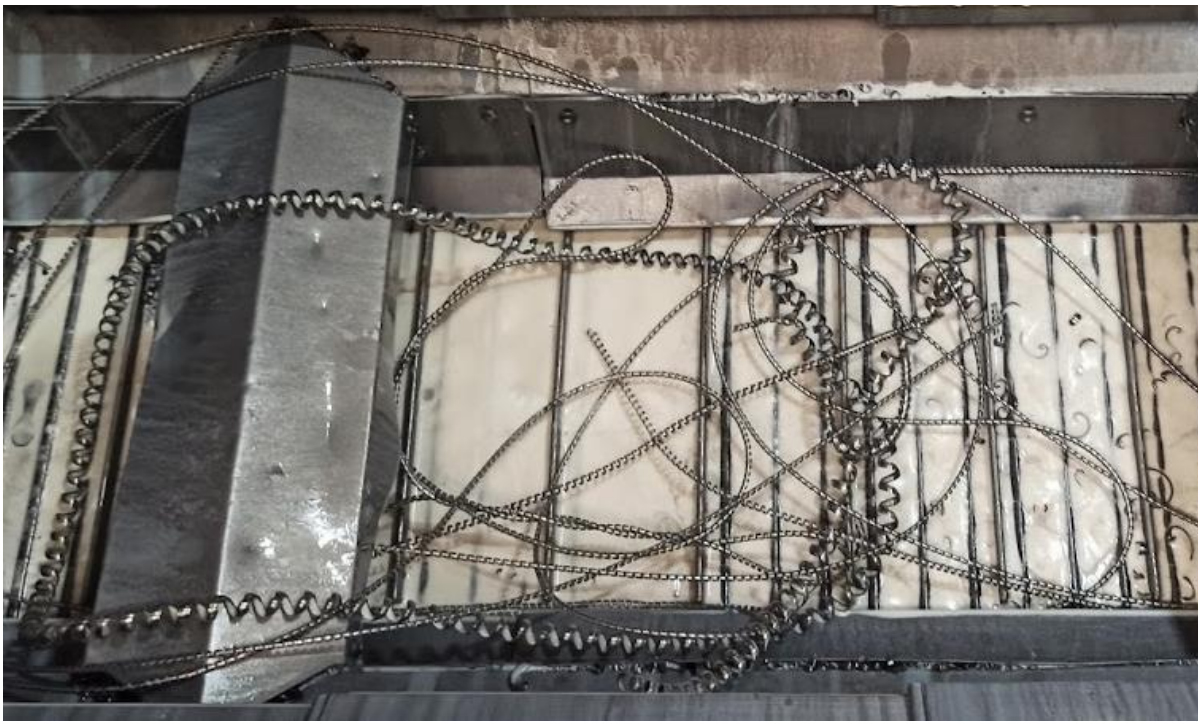


Figure 3.9.1.2 Mostly unfragmented chips after grooving with grooving insert.

It is recommended to rather use the new VNMG tool insert with improved cutting parameters. Results when using the contouring tool should be significantly better and easily achievable.

Using a grooving insert could be a sufficient solution if well optimised when it comes to chip fragmentation. Chip fragmentation optimisation during grooving is usually more challenging than for external turning.

3.9.2 Chip peck cycle drilling

As long chip in drilling weren't very problematic for evacuation and vibration assisted drilling is an expensive technology, a more traditional technique is preferable for this industrial context. Company Mitis was contacted considering budget for problems encountered

Chip peck cycles were introduced in the theoretical analysis.

When introducing the chip peck cycle, the chips shorter but the machining time is longer.

Figure 3.9.2.1 Chips after normal drilling (without chick peck cycle).

Figure 3.9.2.2 Chips obtained using chip peck cycle during drilling G3 (all three chips are from the same cycle).

All three chips presented in the figure above were from the same chip peck cycle. The longest of those three chips was about three times shorter than the chip obtained using classic drilling.

3.10 OVERALL RESULTS OF EXPERIMENTATIONS, RECOMMENDATIONS

Overall experimental results and their conclusion and recommendations are listed in the table below.

Table 3.9.2.1 Resume of solutions for problems observed in production based on experimentations.

OP	Phase	Tool	Problem	Proposed solution	Experimentation	Result	Recommendations
1	External diameter roughing	T1001, Rouging insert CNMG16	long unfragmented chips	Elaborate chip fragmentation study and try new cutting inserts for roughing	Chip fragmentation during roughing and semi-finishing with geometry CNMG	New cutting insert with better chip fragmentation and lower specific cutting pressure, increase in chip removal rate and gain in machining time as bonus	Implement new cutting insert: CNMG 16 06 16-RP5 WPP10S, investigate tool life in function of cutting speed, find optimum cutting speed
1	Finishing + groove turning	T1066, finishing insert VNMG12	long unfragmented chips, stuck on the tool and on the workpiece	Elaborate chip fragmentation study and try new cutting inserts for finishing	Chip fragmentation during roughing and semi-finishing with geometry VNMG	New cutting insert with better chip fragmentation even at low depths of cut and low feeds	Implement new cutting insert: VNMG 16 04 04-FP5 WPP20S, investigate tool life in function of cutting speed, find optimum cutting speed
1	boring (finishing)	T1006, insert CNMG12	predrilled hole before turning left uneven bottom surface, boring tool insert often broke during the finishing of	add a pass of finishing (integrate new finishing tool)	Experimentation of boring + change of strategy	Cutting conditions found that produce acceptable chips	add a pass of finishing (integrate new finishing tool) and use adapted cutting conditions found during the experimentations
1	external thread turning	T1004	long unfragmented chips, blocking chip conveyor, must be cut manually with pincers	try different infeed methods	External thread turning experimentations	Modified flank infeed produces acceptable chips that can be evacuated by chip conveyor easily	Always use modified flank infeed for thread turning of external thread of locking bolts

OP	Phase	Tool	Problem	Proposed solution	Experimentation	Result	Recommendations
2	cylindrical turning - roughing	T1001, Rouging insert CNMG12	chip in form of a ring, need to be manually taken out	machine the contour in opposite sense, pushing the ring into to the left side and evacuating it	Chip fragmentation during roughing and semi-finishing with geometry CNMG	same as for roughing in operation 1	same as for roughing in operation 1 + change direction of the contour machining
2	boring (roughing)	T1006, insert CNMG12	unfragmented chips stuck on the tool and workpiece	Elaborate chip fragmentation study and try new cutting inserts for boring	Experimentation of boring + change of strategy	Cutting conditions found that produce acceptable chips	Keep original cutting insert but modify cutting conditions accordingly to the experimental results
2	thread tapping	cutting tap	unfragmented chips stuck on the tool every time	replace taps with thread milling tools that produce fragmented chips	Experimentation of thread milling with solid milling cutter	Facets of vibrations present but thread is acceptable	Employ thread milling strategy and the milling tool, but continue to search for cutting conditions that would minimize vibrations
2	internal thread turning	T1029, thread turning insert	Chips long, stuck in the threaded hole, needed to be taken out manually, facets on the thread	replace thread turning with thread milling tools that produce fragmented chips	Experimentation of thread milling with milling cutter with cutting inserts	Excellent results, good surface quality, facets eliminated, machining time slightly longer than for thread turning but comparable	Employ thread milling strategy and the milling tool with cutting inserts

4 DISCUSSION

Notes and recommendations for future improvements were already stated at the end of every chapter about the experimentations in their final section with overall results.

Even though the main goal of this study was not an economical optimisation, in an industrial context savings in production cost would be convenient.

The roughing operation of the external surface of the locking bolts represents about a third of the machining process and therefore represents an important part of overall production cost. The roughing operation of the locking bolt is an economically important operation. The roughing operation should be studied more, esp. the magnitude of cutting speed and its relation to tool life, affecting the machining costs. The value of the cutting speed set during the experimentations should be used as default value and several different cutting speeds should be tested in regard of the tool life.

In general, increases in cutting speed decrease tool life, but the part is machined quicker. Economically optimal value of cutting speed $v_{c,optimal}$ should be searched as a value that compensates shorter tool life by having shorter machining cycle time [22].

Once tool life of cutting inserts is known, automatic tool change can be programmed at correct intervals. Automatic tool changer can take twin tooling for the same tool if needed.

All changes to machining strategies, new tools and new cutting conditions need to be implemented in production. Changes need to be done in CAM programs. It is recommended to implement all changes on a chosen model of the locking bolt at first and evaluate if all problems during machining were eliminated or if any other changes are needed. Once a choosing locking bolt machining is confirmed successfully, the strategies and cutting conditions can be expanded to all models of the locking bolts.

Once the new CAM programs are generated and the resulting NC programs are tested in productions with confirmation of good chip evacuation for every machining phase, robotization can be considered as investment.

Study of return of investment is going to be evaluated in a project for Industrialisation Team of the company. The future project that was determined as continuation of this thesis. Refit of the CNC machine is necessary before implementing an automated workpiece feed system. Future increase in the size of series of locking bolts presents a possibly quick return of investment.

CONCLUSIONS

New cutting tools and new cutting strategies have been tested to get acceptable chip fragmentation during machining providing short chips that are easy to evacuate and transport.

The chip fragmentation was optimized for several technologies:

- the cylindrical turning roughing with CNMG cutting inserts where a new cutting insert was recommended,
- the finishing and contouring with VNMG cutting insert where a new cutting insert was also recommended,
- the boring operation with CNMG insert where the original insert was preserved, but the cutting conditions were changed to improve the results,
- the external thread turning - by changing infeed mode to modified flank infeed mode,
- the internal thread turning by replacing the turning strategy by more productive milling using special thread milling cutters and cutting inserts,
- the internal thread tapping by substituting the tapping tools by solid thread milling cutters and machining strategies.

Finally, a very acceptable chip fragmentation and chip evacuation have been achieved. Moreover, the following beneficial results of machining with impact on economy have been confirmed:

- the new cutting inserts and optimised cutting conditions for roughing turning resulted in significantly shorter machining times. For the locking bolt HP3 the reduction in machining time was at least 45% (using cutting speed ≥ 130 m/min) and, for the locking bolt HP6 the decrease of machining time was at least 27%.
- Moreover, significantly less cutting power was needed in comparison with the original roughing cutting inserts;
- a very modern strategy of pocket milling using the trochoidal trajectories resulted in significantly shorter machining time, so the reduction of the time was within 60-80%.

The optimisations present the first but very crucial step for expected automation of the machining process. The excellent chip fragmentations eliminate troubles resulting in CNC machine interruption when the operator must get rid of the chip winding around the tool, evacuate chip clogging of workpiece, or to release the chip conveyor. The results of the diploma work support high stability and continuity of production.

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	Unit	Description
ATC	[-]	Automatic Tool Changer
CAD	[-]	Computer-Aided Design
CAM	[-]	Computer-Aided Manufacturing
CLF	[-]	Cooling and lubrification fluids
CCW	[-]	Counterclockwise
CNC	[-]	Computer Numerical Control
CW	[-]	Clockwise
ISO	[-]	International Organization of Standardization
Max.	[-]	Maximum/Maximal
NC	[-]	Numerical Control
NMR	[%]	Nominal Machinability Rating
DIN	[-]	Deutsche Industrie-Norm – German industrial norm
MMR	[unit/min]	Material Removal Rate

Symbol	Unit	Description
A, B, C	[-]	Rotational axes of a machine
a_e	[mm]	radial depth of cut
a_p	[mm]	axial depth of cut
D	[mm]	Tool diameter
d	[mm]	Workpiece diameter
d_c	[mm]	Counterbore diameter
f	[mm]	Feed rate
G…	[-]	Preparatory function in ISO code for NC programming

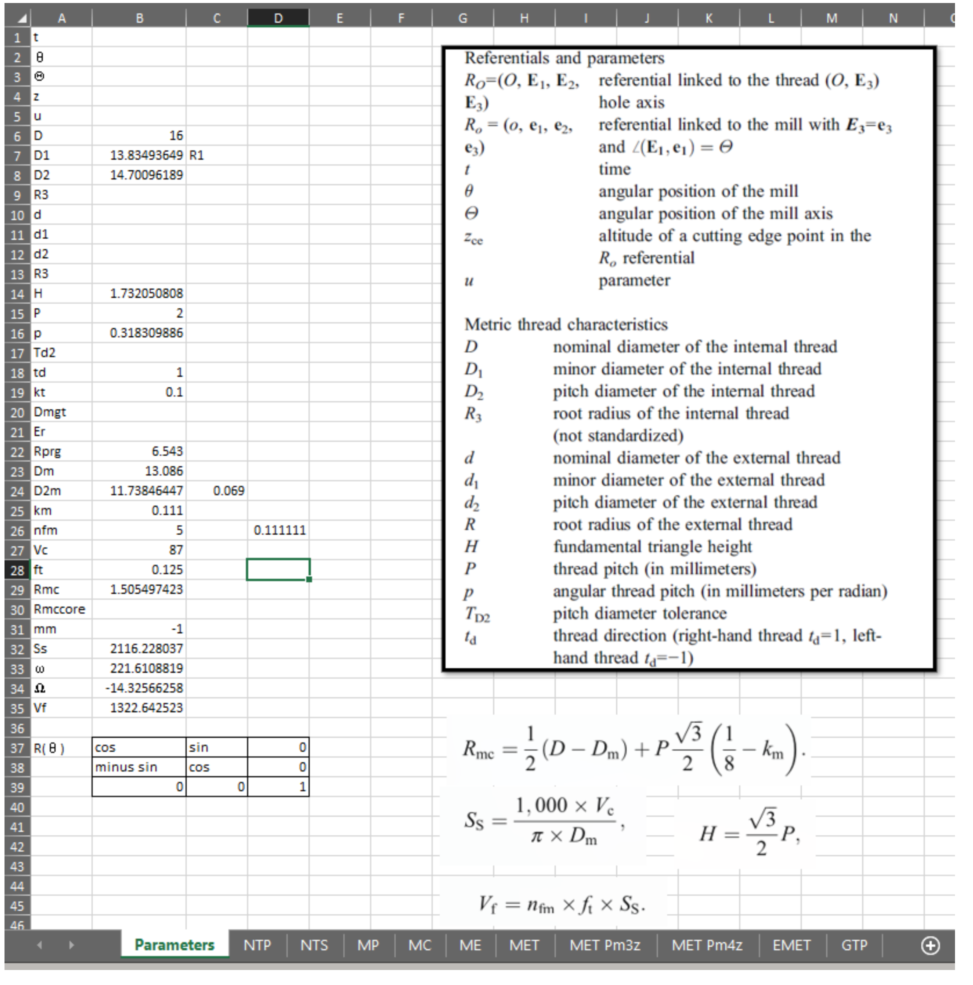
HB	[-]	Hardness of Brinell
HL	[-]	Hardness of Leeb
HRC		Hardness of Rockwell
HV		Hardness of Vickers
L	[mm]	Length
M	[-]	Machine reference point
M…	[-]	Auxiliary function in ISO code for NC programming
N…	[-]	block number in ISO code for NC programming NC programming
P	[-]	Tool setup point
R	[-]	Reference point
$\mathbf{R_m}$	[MPa]	Tensile strength
$\mathbf{r_t}$	[mm]	Radius of the tool
t	[mm]	Thickness
$\mathbf{v_c}$	$[m.min^{-1}]$	Cutting speed
$\mathbf{v_f}$	$[m.min^{-1}]$	Feed speed
$\mathbf{a_p}$	[mm]	Depth of cut
ξ **(MMR) (Q)**	[unit/min]	Material removal rate
wt.	[kg]	weight
X, Y, Z	[-]	Translational axes of a machine

LIST OF APPENDICES

APPENDICES:

1) ALGORITHM OF CALCULATION OF INTERFERENCES DURING INTERNAL THREAD MILLING

Algorithm for calculation od interferences according to literature (FROMENTIN, Guillaume and Gérard POULACHON, [53]) was calculated using a spread sheet which lists follow in the figures below.



	A	B	C	D
1	t			
2	θ			
3	Θ			
4	z			
5	u			
6	D	16		
7	D1	13.83493649	R1	
8	D2	14.70096189		
9	R3			
10	d			
11	d1			
12	d2			
13	R3			
14	H	1.732050808		
15	P	2		
16	p	0.318309886		
17	Td2			
18	td	1		
19	kt	0.1		
20	Dmgt			
21	Er			
22	Rprg	6.543		
23	Dm	13.086		
24	D2m	11.73846447	0.069	
25	km	0.111		
26	nfm	5		0.111111
27	Vc	87		
28	ft	0.125		
29	Rmc	1.505497423		
30	Rmccore			
31	mm	-1		
32	Ss	2116.228037		
33	ω	221.6108819		
34	Ω	-14.32566258		
35	Vf	1322.642523		
36				
37	R(θ)	cos	sin	0
38		minus sin	cos	0
39		0	0	1

Referentials and parameters

$R_O=(O, \mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3)$	referential linked to the thread $(O, \mathbf{E}_3)$ hole axis
$R_o=(o, \mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$	referential linked to the mill with $\mathbf{E}_3$=$\mathbf{e}_3$ and $\angle(\mathbf{E}_1, \mathbf{e}_1) = \Theta$
t	time
θ	angular position of the mill
Θ	angular position of the mill axis
z_{ce}	altitude of a cutting edge point in the R_o referential
u	parameter

Metric thread characteristics

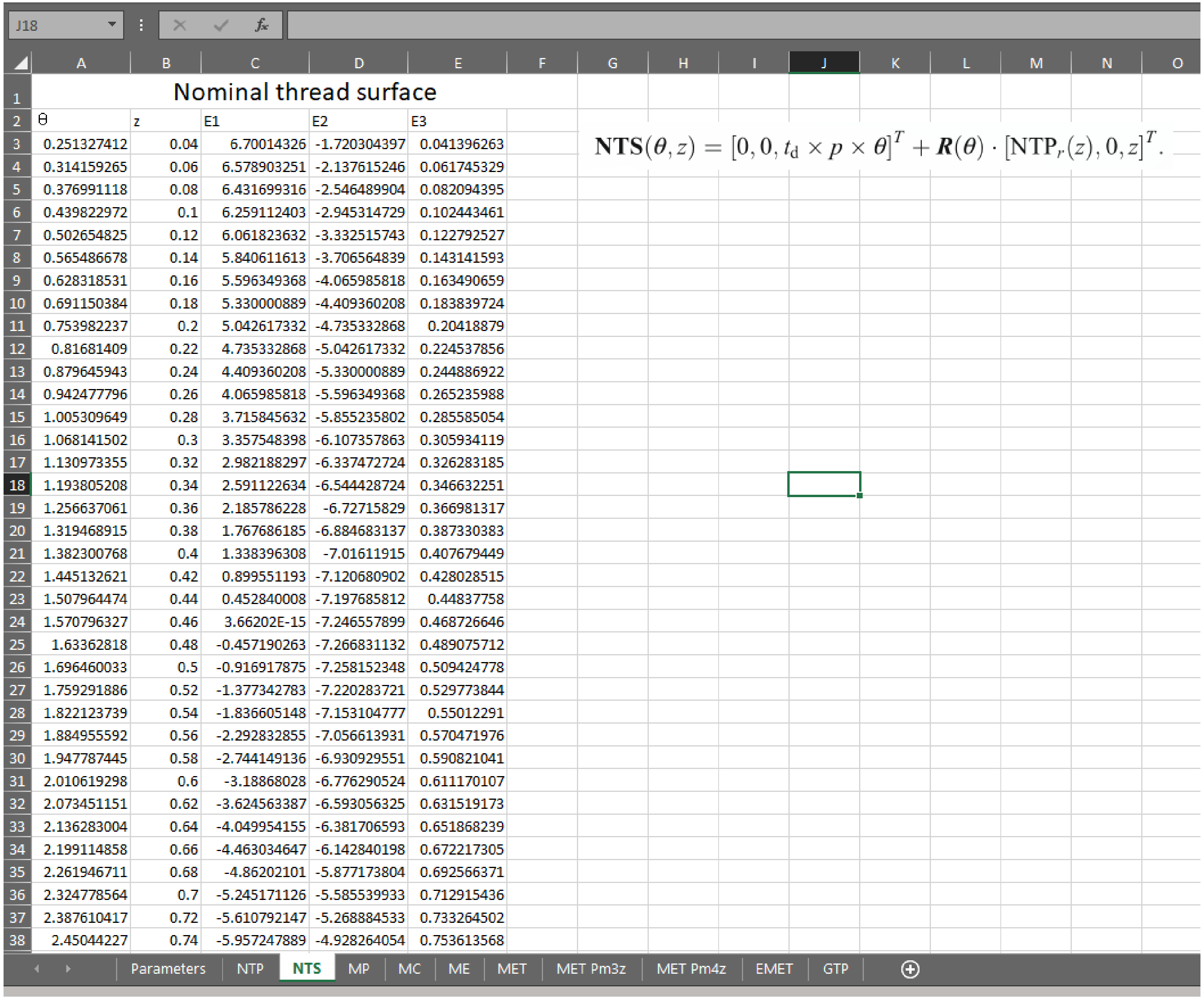
D	nominal diameter of the internal thread
D_1	minor diameter of the internal thread
D_2	pitch diameter of the internal thread
R_3	root radius of the internal thread (not standardized)
d	nominal diameter of the external thread
d_1	minor diameter of the external thread
d_2	pitch diameter of the external thread
R	root radius of the external thread
H	fundamental triangle height
P	thread pitch (in millimeters)
p	angular thread pitch (in millimeters per radian)
T_{D2}	pitch diameter tolerance
t_d	thread direction (right-hand thread t_d=1, left-hand thread t_d=−1)

$$R_{mc} = \frac{1}{2}(D - D_m) + P\frac{\sqrt{3}}{2}\left(\frac{1}{8} - k_m\right).$$

$$S_S = \frac{1,000 \times V_c}{\pi \times D_m}, \qquad H = \frac{\sqrt{3}}{2}P,$$

$$V_f = n_{fm} \times f_t \times S_S.$$

Figure 1 Entry parameters.



Nominal thread surface

θ	z	E1	E2	E3
0.251327412	0.04	6.70014326	-1.720304397	0.041396263
0.314159265	0.06	6.578903251	-2.137615246	0.061745329
0.376991118	0.08	6.431699316	-2.546489904	0.082094395
0.439822972	0.1	6.259112403	-2.945314729	0.102443461
0.502654825	0.12	6.061823632	-3.332515743	0.122792527
0.565486678	0.14	5.840611613	-3.706564839	0.143141593
0.628318531	0.16	5.596349368	-4.065985818	0.163490659
0.691150384	0.18	5.330000889	-4.409360208	0.183839724
0.753982237	0.2	5.042617332	-4.735332868	0.20418879
0.81681409	0.22	4.735332868	-5.042617332	0.224537856
0.879645943	0.24	4.409360208	-5.330000889	0.244886922
0.942477796	0.26	4.065985818	-5.596349368	0.265235988
1.005309649	0.28	3.715845632	-5.855235802	0.285585054
1.068141502	0.3	3.357548398	-6.107357863	0.305934119
1.130973355	0.32	2.982188297	-6.337472724	0.326283185
1.193805208	0.34	2.591122634	-6.544428724	0.346632251
1.256637061	0.36	2.185786228	-6.72715829	0.366981317
1.319468915	0.38	1.767686185	-6.884683137	0.387330383
1.382300768	0.4	1.338396308	-7.01611915	0.407679449
1.445132621	0.42	0.899551193	-7.120680902	0.428028515
1.507964474	0.44	0.452840008	-7.197685812	0.44837758
1.570796327	0.46	3.66202E-15	-7.246557899	0.468726646
1.63362818	0.48	-0.457190263	-7.266831132	0.489075712
1.696460033	0.5	-0.916917875	-7.258152348	0.509424778
1.759291886	0.52	-1.377342783	-7.220283721	0.529773844
1.822123739	0.54	-1.836605148	-7.153104777	0.55012291
1.884955592	0.56	-2.292832855	-7.056613931	0.570471976
1.947787445	0.58	-2.744149136	-6.930929551	0.590821041
2.010619298	0.6	-3.18868028	-6.776290524	0.611170107
2.073451151	0.62	-3.624563387	-6.593056325	0.631519173
2.136283004	0.64	-4.049954155	-6.381706593	0.651868239
2.199114858	0.66	-4.463034647	-6.142840198	0.672217305
2.261946711	0.68	-4.86202101	-5.877173804	0.692566371
2.324778564	0.7	-5.245171126	-5.585539933	0.712915436
2.387610417	0.72	-5.610792147	-5.268884533	0.733264502
2.45044227	0.74	-5.957247889	-4.928264054	0.753613568

$$\mathbf{NTS}(\theta, z) = [0, 0, t_d \times p \times \theta]^T + \boldsymbol{R}(\theta) \cdot [\mathrm{NTP}_r(z), 0, z]^T.$$

Figure 2 Calculation of nominal thread surface.

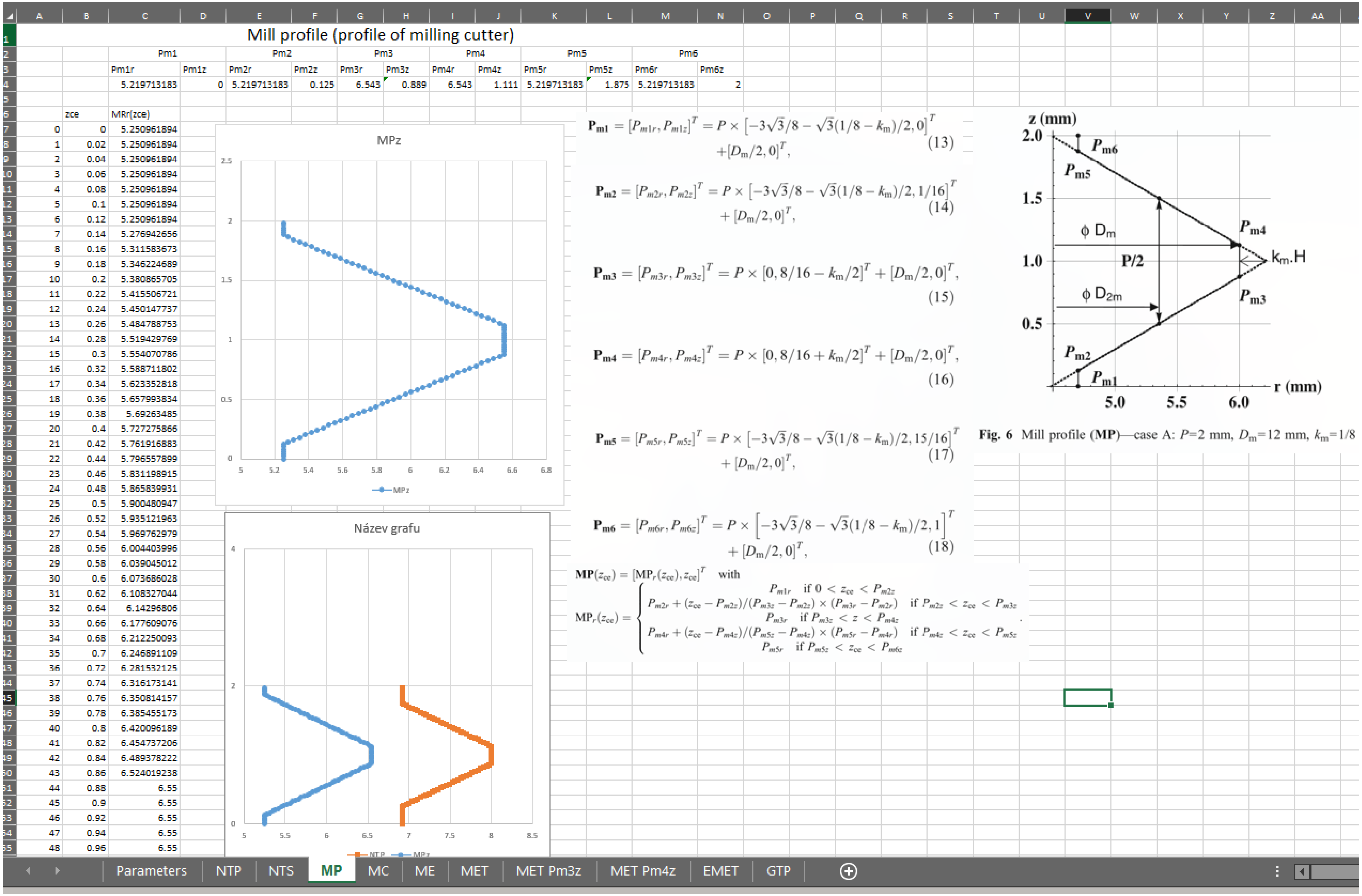
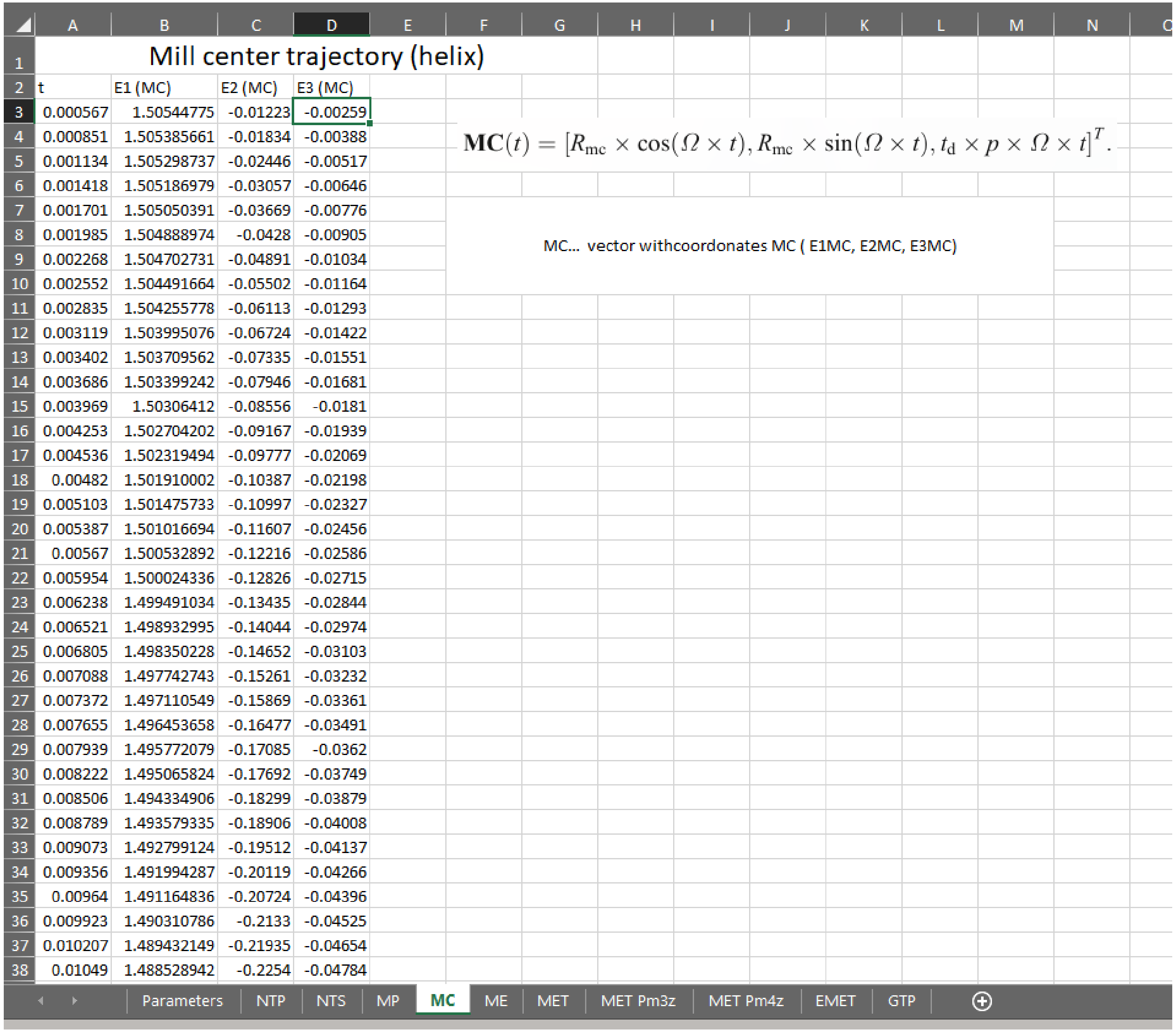


Figure 3 Calculation of profile of milling cutter.



Mill center trajectory (helix)

t	E1 (MC)	E2 (MC)	E3 (MC)
0.000567	1.50544775	-0.01223	-0.00259
0.000851	1.505385661	-0.01834	-0.00388
0.001134	1.505298737	-0.02446	-0.00517
0.001418	1.505186979	-0.03057	-0.00646
0.001701	1.505050391	-0.03669	-0.00776
0.001985	1.504888974	-0.0428	-0.00905
0.002268	1.504702731	-0.04891	-0.01034
0.002552	1.504491664	-0.05502	-0.01164
0.002835	1.504255778	-0.06113	-0.01293
0.003119	1.503995076	-0.06724	-0.01422
0.003402	1.503709562	-0.07335	-0.01551
0.003686	1.503399242	-0.07946	-0.01681
0.003969	1.50306412	-0.08556	-0.0181
0.004253	1.502704202	-0.09167	-0.01939
0.004536	1.502319494	-0.09777	-0.02069
0.00482	1.501910002	-0.10387	-0.02198
0.005103	1.501475733	-0.10997	-0.02327
0.005387	1.501016694	-0.11607	-0.02456
0.00567	1.500532892	-0.12216	-0.02586
0.005954	1.500024336	-0.12826	-0.02715
0.006238	1.499491034	-0.13435	-0.02844
0.006521	1.498932995	-0.14044	-0.02974
0.006805	1.498350228	-0.14652	-0.03103
0.007088	1.497742743	-0.15261	-0.03232
0.007372	1.497110549	-0.15869	-0.03361
0.007655	1.496453658	-0.16477	-0.03491
0.007939	1.495772079	-0.17085	-0.0362
0.008222	1.495065824	-0.17692	-0.03749
0.008506	1.494334906	-0.18299	-0.03879
0.008789	1.493579335	-0.18906	-0.04008
0.009073	1.492799124	-0.19512	-0.04137
0.009356	1.491994287	-0.20119	-0.04266
0.00964	1.491164836	-0.20724	-0.04396
0.009923	1.490310786	-0.2133	-0.04525
0.010207	1.489432149	-0.21935	-0.04654
0.01049	1.488528942	-0.2254	-0.04784

$$\mathbf{MC}(t) = [R_{mc} \times \cos(\Omega \times t), R_{mc} \times \sin(\Omega \times t), t_d \times p \times \Omega \times t]^T.$$

MC... vector withcoordonates MC (E1MC, E2MC, E3MC)

Figure 4 Calculation of mill central trajectory

	A	B	C	D	E	F
1	Mill envelope (envelope generated by the milling cutter)					
2	t	θ	zce	E1 (ME)	E2 (ME)	E3 (ME)
3	0.00085057	0.188495559	0.02	6.663338583	0.018049251	0.016121401
4	0.001134093	0.251327412	0.04	6.591292007	0.031939006	0.034828535
5	0.001417617	0.314159265	0.06	6.499148506	0.049607221	0.053535668
6	0.00170114	0.376991118	0.08	6.387271289	0.070912931	0.072242802
7	0.001984663	0.439822972	0.1	6.256101348	0.09568557	0.090949936
8	0.002268187	0.502654825	0.12	6.106155715	0.123726003	0.109657069
9	0.00255171	0.565486678	0.14	5.95996171	0.155573673	0.128364203
10	0.002835233	0.628318531	0.16	5.801417236	0.190856439	0.147071337
11	0.003118757	0.691150384	0.18	5.623331997	0.229143383	0.16577847
12	0.00340228	0.753982237	0.2	5.42619185	0.27017695	0.184485604
13	0.003685803	0.81681409	0.22	5.210568695	0.313670003	0.203192737
14	0.003969326	0.879645943	0.24	4.977119036	0.359307159	0.221899871
15	0.00425285	0.942477796	0.26	4.726582143	0.406746312	0.240607005
16	0.004536373	1.005309649	0.28	4.459777857	0.455620374	0.259314138
17	0.004819896	1.068141502	0.3	4.177604009	0.505539187	0.278021272
18	0.00510342	1.130973355	0.32	3.881033484	0.556091632	0.296728406
19	0.005386943	1.193805208	0.34	3.571110934	0.606847906	0.315435539
20	0.005670466	1.256637061	0.36	3.248949141	0.657361957	0.334142673
21	0.00595399	1.319468915	0.38	2.915725055	0.707174076	0.352849807
22	0.006237513	1.382300768	0.4	2.572675515	0.755813619	0.37155694
23	0.006521036	1.445132621	0.42	2.22109267	0.802801858	0.390264074
24	0.00680456	1.507964474	0.44	1.86231911	0.847654934	0.408971208
25	0.007088083	1.570796327	0.46	1.497742743	0.889886908	0.427678341
26	0.007371606	1.63362818	0.48	1.128791413	0.929012885	0.446385475
27	0.00765513	1.696460033	0.5	0.756927301	0.964552198	0.465092609
28	0.007938653	1.759291886	0.52	0.383641123	0.99603163	0.483799742
29	0.008222176	1.822123739	0.54	0.010446143	1.022988661	0.502506876
30	0.0085057	1.884955592	0.56	-0.36112797	1.044974722	0.52121401
31	0.008789223	1.947787445	0.58	-0.729541409	1.061558431	0.539921143
32	0.009072746	2.010619298	0.6	-1.09325061	1.072328793	0.558628277
33	0.00935627	2.073451151	0.62	-1.450714709	1.07689835	0.577335411
34	0.009639793	2.136283004	0.64	-1.800402051	1.07490626	0.596042544
35	0.009923316	2.199114858	0.66	-2.140796724	1.066021281	0.614749678
36	0.01020684	2.261946711	0.68	-2.47040509	1.049944648	0.633456811
37	0.010490363	2.324778564	0.7	-2.787762288	1.026412814	0.652163945
38	0.010773886	2.387610417	0.72	-3.091438673	0.995200056	0.670871079

$$\mathbf{ME}(t,\theta,z_{ce}) = \mathbf{MC}(t) + \mathbf{R}(\theta)\cdot[\mathrm{MP}_r(z_{ce}),0,z_{ce}]^T.$$

Parameters | NTP | NTS | MP | MC | ME | MET | MET Pm3z | MET Pm4z | EMET | GTP

Figure 5 Calculation of mill envelope.

Mill envelope trace (projection of circle in ME)

t	θ	zce	E1	E3
0.00085057	0.18805429	0.02	6.66377226	0.016121401
0.001134093	0.186869131	0.04	6.664845132	0.034828535
0.001417617	0.185684316	0.06	6.66588559	0.053535668
0.00170114	0.184499862	0.08	6.666893624	0.072242802
0.001984663	0.183315787	0.1	6.667869225	0.090949936
0.002268187	0.182132109	0.12	6.668812383	0.109657069
0.00255171	0.180048174	0.14	6.696132897	0.128364203
0.002835233	0.177692319	0.16	6.732204401	0.147071337
0.003118757	0.175368163	0.18	6.768221359	0.16577847
0.00340228	0.173075079	0.2	6.804184373	0.184485604
0.003685803	0.17081246	0.22	6.840094028	0.203192737
0.003969326	0.168579712	0.24	6.875950892	0.221899871
0.00425285	0.166376262	0.26	6.911755521	0.240607005
0.004536373	0.164201547	0.28	6.947508455	0.259314138
0.004819896	0.162055023	0.3	6.983210222	0.278021272
0.00510342	0.159936159	0.32	7.018861334	0.296728406
0.005386943	0.157844437	0.34	7.054462295	0.315435539
0.005670466	0.155779354	0.36	7.090013592	0.334142673
0.00595399	0.15374042	0.38	7.125515703	0.352849807
0.006237513	0.151727157	0.4	7.160969093	0.37155694
0.006521036	0.1497391	0.42	7.196374217	0.390264074
0.00680456	0.147775793	0.44	7.231731519	0.408971208
0.007088083	0.145836796	0.46	7.267041434	0.427678341
0.007371606	0.143921676	0.48	7.302304384	0.446385475
0.00765513	0.142030013	0.5	7.337520784	0.465092609
0.007938653	0.140161398	0.52	7.372691039	0.483799742
0.008222176	0.138315429	0.54	7.407815546	0.502506876
0.0085057	0.136491717	0.56	7.442894691	0.52121401
0.008789223	0.13468988	0.58	7.477928853	0.539921143
0.009072746	0.132909548	0.6	7.512918403	0.558628277
0.00935627	0.131150356	0.62	7.547863704	0.577335411
0.009639793	0.129411951	0.64	7.582765112	0.596042544
0.009923316	0.127693987	0.66	7.617622974	0.614749678
0.01020684	0.125996126	0.68	7.652437632	0.633456811
0.010490363	0.124318038	0.7	7.687209418	0.652163945
0.010773886	0.122659401	0.72	7.721938661	0.670871079

$$\mathbf{ME}(t,\theta,z_{\text{ce}})\cdot\mathbf{E_2}=0$$

$$\Leftrightarrow \theta(t,z_{\text{ce}}) = -\arcsin(R_{\text{mc}}\times\sin(\Omega\times t)/\text{MP}_r(z_{\text{ce}})),$$

$$\mathbf{MET}(t,z_{\text{ce}}) = [\mathbf{ME}(t,\theta(t,z_{\text{ce}}),z_{\text{ce}})\cdot\mathbf{E}_1, \mathbf{ME}(t,\theta(t,z_{\text{ce}}),z_{\text{ce}})\cdot\mathbf{E}_3]^T.$$

Parameters | NTP | NTS | MP | MC | ME | MET | MET Pm3z | MET Pm4z | EMET | GTP

Figure 6 Calculation of mill envelope trace.

Envelope of the mill envelope trace in plane (O, E1, E3)

t	θ	zce	E1	E3	
0.000283523	0.190425568	0.02	6.66142998	0.016121401	-0.256038265
0.000567047	0.189239775	0.04	6.662517973	0.034828535	-0.254950272
0.00085057	0.18805429	0.06	6.663573579	0.053535668	-0.253894666
0.001134093	0.186869131	0.08	6.664596786	0.072242802	-0.252871459
0.001417617	0.185684316	0.1	6.665587584	0.090949936	-0.251880661
0.00170114	0.184499862	0.12	6.666545963	0.109657069	-0.250922282
0.001984663	0.18240307	0.14	6.693893176	0.128364203	-0.223575069
0.002268187	0.180030523	0.16	6.729994845	0.147071337	-0.1874734
0.00255171	0.177689879	0.18	6.76604157	0.16577847	-0.151426675
0.002835233	0.175380509	0.2	6.80203396	0.184485604	-0.115434285
0.003118757	0.173101798	0.22	6.837972607	0.203192737	-0.079495638
0.00340228	0.170853152	0.24	6.873858088	0.221899871	-0.043610157
0.003685803	0.168633989	0.26	6.909690965	0.240607005	-0.025097788
0.003969326	0.166443745	0.28	6.945471787	0.259314138	-0.023957983
0.00425285	0.16428187	0.3	6.981201087	0.278021272	-0.022869699
0.004536373	0.162147831	0.32	7.016879385	0.296728406	-0.021832417
0.004819896	0.160041105	0.34	7.052507189	0.315435539	-0.020845629
0.00510342	0.157961185	0.36	7.088084995	0.334142673	-0.019908839
0.005386943	0.155907579	0.38	7.123613285	0.352849807	-0.019021565
0.005670466	0.153879803	0.4	7.159092532	0.37155694	-0.018183334
0.00595399	0.15187739	0.42	7.194523196	0.390264074	-0.017393686
0.006237513	0.149899882	0.44	7.229905726	0.408971208	-0.016652172
0.006521036	0.147946833	0.46	7.265240562	0.427678341	-0.015958353
0.00680456	0.14601781	0.48	7.300528133	0.446385475	-0.015311798
0.007088083	0.144112388	0.5	7.335768858	0.465092609	-0.01471209
0.007371606	0.142230155	0.52	7.370963146	0.483799742	-0.014158817
0.00765513	0.140370708	0.54	7.4061114	0.502506876	-0.013651579
0.007938653	0.138533652	0.56	7.441214011	0.52121401	-0.013189985
0.008222176	0.136718606	0.58	7.476271362	0.539921143	-0.01277365
0.0085057	0.134925194	0.6	7.511283829	0.558628277	-0.012402199
0.008789223	0.133153051	0.62	7.546251779	0.577335411	-0.012075265
0.009072746	0.13140182	0.64	7.581175571	0.596042544	-0.011792489
0.00935627	0.129671154	0.66	7.616055559	0.614749678	-0.011553518
0.009639793	0.127960711	0.68	7.650892085	0.633456811	-0.011358007
0.009923316	0.12627016	0.7	7.68568549	0.652163945	-0.011205619
0.01020684	0.124599176	0.72	7.720436102	0.670871079	-0.011096022

$$\mathrm{DET}\left[\frac{\partial(\mathbf{MET}(t,\, z_{ce})}{\partial t} \quad \frac{\partial(\mathbf{MET}(t,\, z_{ce})}{\partial z_{ce}}\right] = 0 \Leftrightarrow t = f(z_{ce}),$$

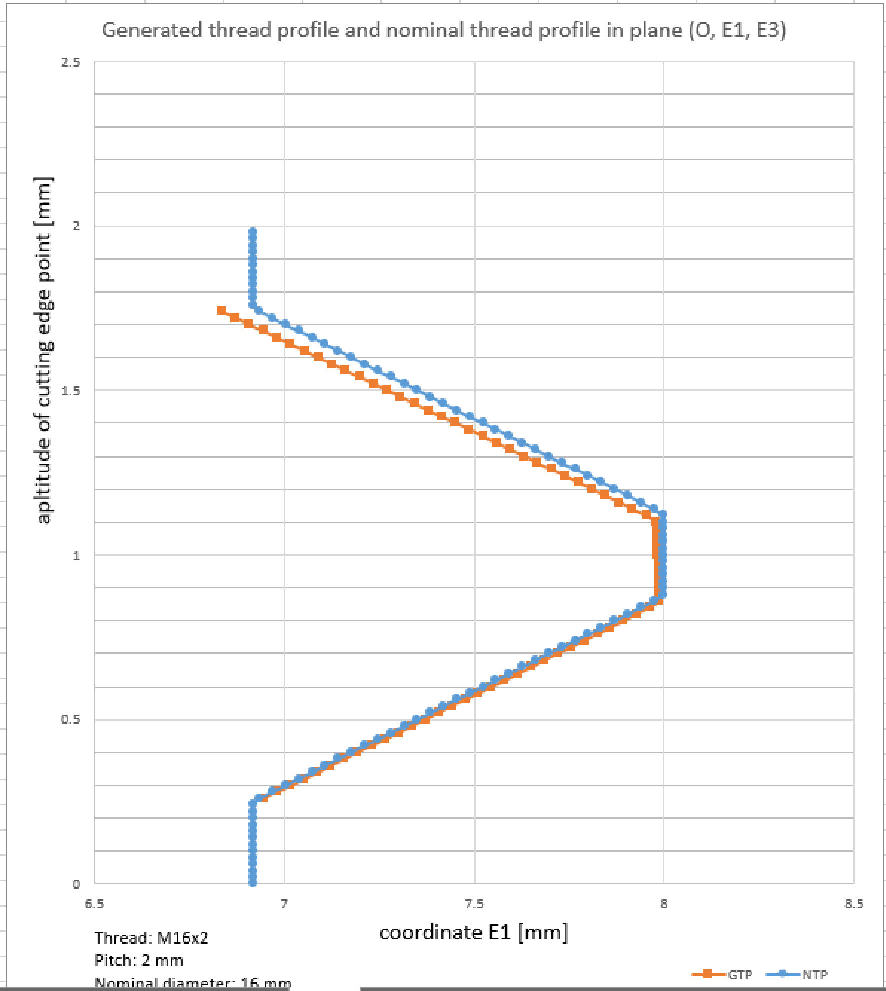
$$\mathbf{EMET}(z_{ce}) = \mathbf{MET}(f(z_{ce}), z_{ce}).$$

Parameters | NTP | NTS | MP | MC | ME | MET | MET Pm3z | MET Pm4z | EMET | GTP

Figure 7 Calculation of mill envelope trace.

zce	GTP		Pm3z	Pm4z	Er	
0	6.66142998	0.034828535	6.664845132	6.664845132	-0.256038265	
0.02	6.662517973	0.053535668	6.66588559	6.66588559	-0.254950272	
0.04	6.663573579	0.072242802	6.666893624	6.666893624	-0.253894666	
0.06	6.664596786	0.090949936	6.667869225	6.667869225	-0.252871459	no
0.08	6.665587584	0.109657069	6.668812383	6.668812383	-0.251880661	overcut
0.1	6.666545963	0.128364203	6.696132897	6.696132897	-0.250922282	COMPUT
0.12	6.693893176	0.147071337	6.732204401	6.732204401	-0.223575069	ABLE,
0.14	6.729994845	0.16577847	6.768221359	6.768221359	-0.1874734	pique,
0.16	6.76604157	0.184485604	6.804184373	6.804184373	-0.151426675	UP TO
0.18	6.80203396	0.203192737	6.840094028	6.840094028	-0.115434285	0.25
0.2	6.837972607	0.221899871	6.875950892	6.875950892	-0.079495638	
0.22	6.873858088	0.240607005	6.911755521	6.911755521	-0.043610157	
0.24	6.909690965	0.259314138	6.947508455	6.947508455	-0.025097788	
0.26	6.945471787	0.278021272	6.983210222	6.983210222	-0.023957983	
0.28	6.981201087	0.296728406	7.018861334	7.018861334	-0.022869699	
0.3	7.016879385	0.315435539	7.054462295	7.054462295	-0.021832417	
0.32	7.052507189	0.334142673	7.090013592	7.090013592	-0.020845629	
0.34	7.088084995	0.352849807	7.125515703	7.125515703	-0.019908839	
0.36	7.123613285	0.37155694	7.160969093	7.160969093	-0.019021565	
0.38	7.159092532	0.390264074	7.196374217	7.196374217	-0.018183334	
0.4	7.194523196	0.408971208	7.231731519	7.231731519	-0.017393686	
0.42	7.229905726	0.427678341	7.267041434	7.267041434	-0.016652172	
0.44	7.265240562	0.446385475	7.302304384	7.302304384	-0.015958353	
0.46	7.300528133	0.465092609	7.337520784	7.337520784	-0.015311798	
0.48	7.335768858	0.483799742	7.372691039	7.372691039	-0.01471209	
0.5	7.370963146	0.502506876	7.407815546	7.407815546	-0.014158817	
0.52	7.4061114	0.52121401	7.442894691	7.442894691	-0.013651579	
0.54	7.441214011	0.539921143	7.477928853	7.477928853	-0.013189985	
0.56	7.476271362	0.558628277	7.512918403	7.512918403	-0.01277365	
0.58	7.511283829	0.577335411	7.547863704	7.547863704	-0.012402199	
0.6	7.546251779	0.596042544	7.582765112	7.582765112	-0.012075265	
0.62	7.581175571	0.614749678	7.617622974	7.617622974	-0.011792489	
0.64	7.616055559	0.633456811	7.652437632	7.652437632	-0.011553518	
0.66	7.650892085	0.652163945	7.687209418	7.687209418	-0.011358007	
0.68	7.68568549	0.670871079	7.721938661	7.721938661	-0.011205619	
0.7	7.720436102	0.689578212	7.756625682	7.756625682	-0.011096022	
0.72	7.755144248	0.708285346	7.791270794	7.791270794	-0.011028893	
0.74	7.789810245	0.72699248	7.825874306	7.825874306	-0.011003912	
0.76	7.824434406	0.745699613	7.860436522	7.860436522	-0.011020768	
0.78	7.859017035	0.764406747	7.894957737	7.894957737	-0.011079154	
0.8	7.893558434	0.783113881	7.929438243	7.929438243	-0.011178771	
0.82	7.928058898	0.801821014	7.963878327	7.963878327	-0.011319324	
0.84	7.962518714	0.820528148	7.989565231	7.989565231	-0.011500524	

$$\mathbf{GTP} = \begin{cases} \mathbf{EMET}(z_{ce}) & \text{if } z_{ce\ \inf.\lim 2} < z_{ce} < P_{m3z} \\ \mathbf{MET}(t, P_{m3z}) & \\ [R_{mc} + P_{m3r}, z_{ce}]^T & \text{if } P_{m3z} < z_{ce} < P_{m4z} \\ \mathbf{MET}(t, P_{m4z}) & \\ \mathbf{EMET}(z_{ce}) & \text{if } z_{ce\ \sup.\lim 2} < z_{ce} < P_{m5z} \end{cases},$$



Parameters NTP NTS MP MC ME MET MET Pm3z MET Pm4z EMET GTP

Figure 8 Calculation of generated thread profile.

2) 3D PRINT OF STUDIED PARTS FOR ILLUSTRATION

For illustration during the presentation of advancements of this project, 3D models of 2 studied components were 3D printed.

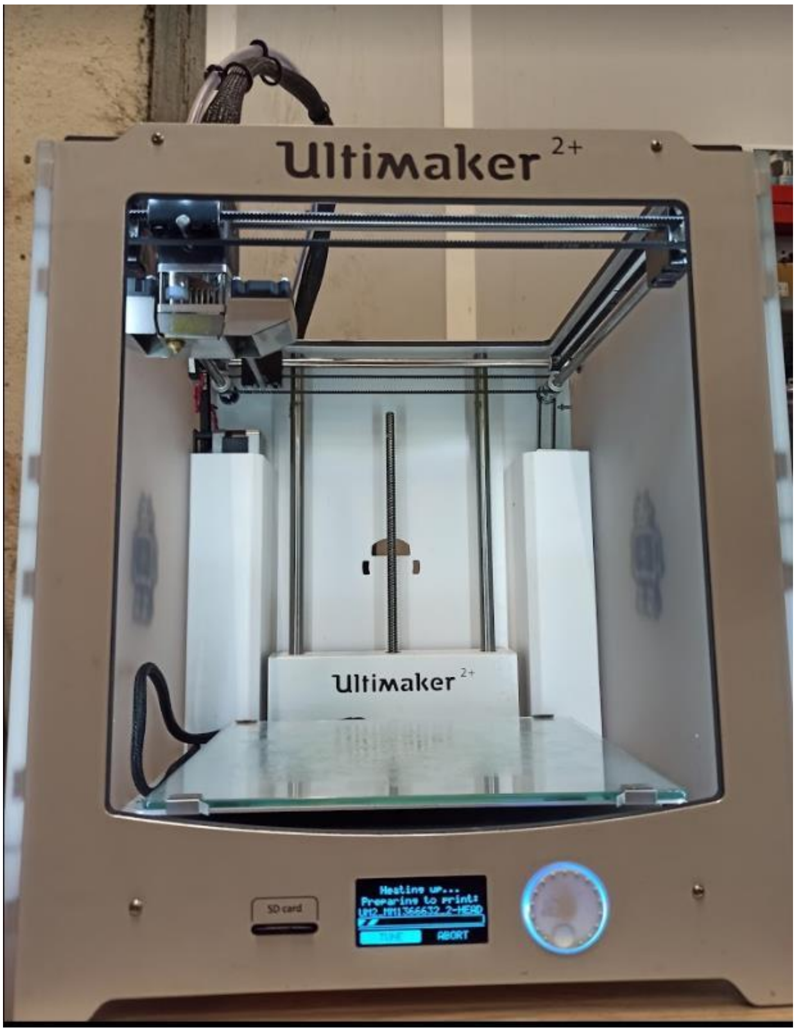


Figure 9 3D printer Ultimaker 2+.

Side view of the 3D printer can be seen in the figure below.

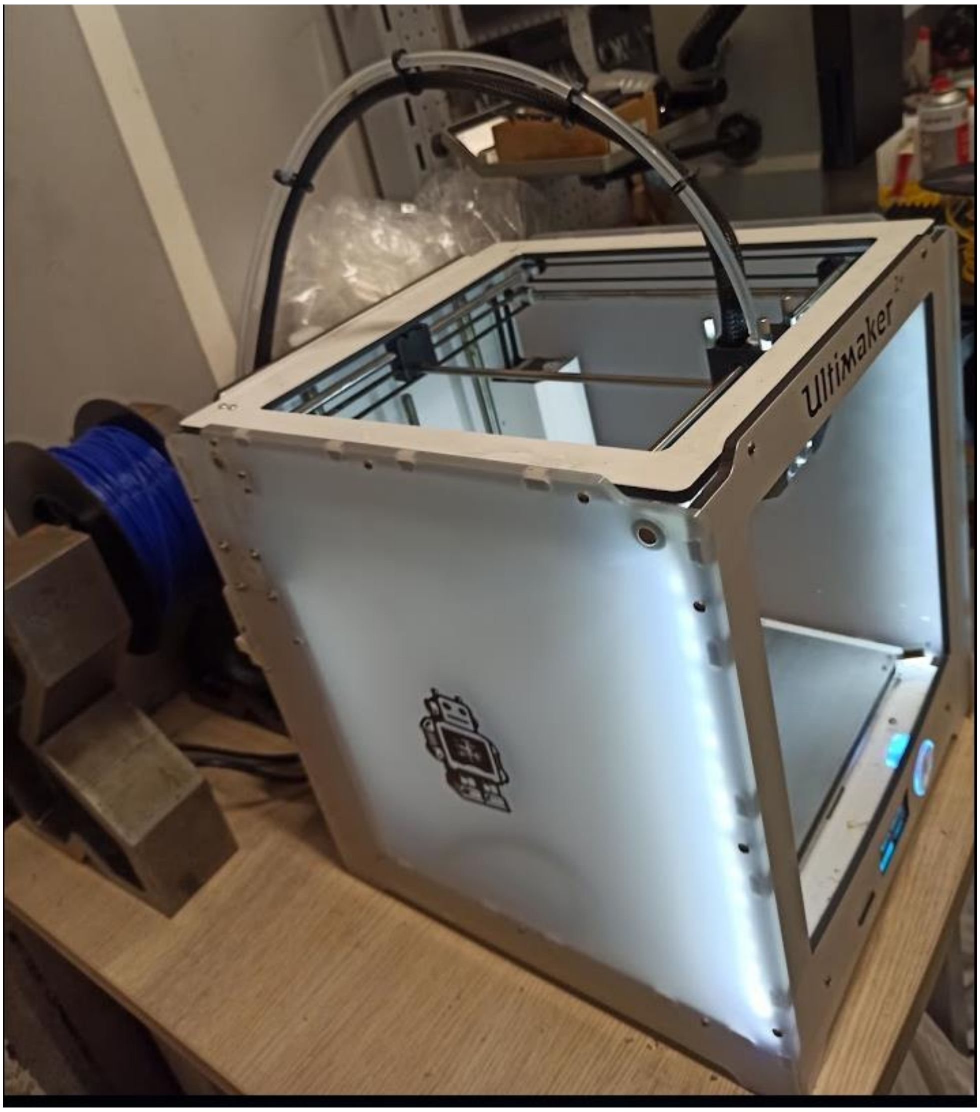


Figure 10 3D printer Ultimaker 2+ in side view with material feed visible.

Printing head bolt HP6:

- Scale 25%,
- Printing time: 6h,
- 3D printer: Ultimaker 2+, nozzle 0.4,
- CAD software: NX – 3D part transport to STL,
- STL model treated for 3D printing in Cura Ultimaker software,
- Material: PLA, colour: yellow.

Printing head bolt HP6:

- Scale 50%
- Printing time: 15h

- 3D printer: Ultimaker 2+, nozzle 0.4,
- CAD software: NX – 3D part transport to STL,
- STL model treated for 3D printing in Cura Ultimaker software,
- Material: PLA, colour: yellow,
- Nozzle: 0.40,
- Material: 25m.

Figure 11 3D printed locking bolt HP6 (50% dimensions) next to the real size locking bolt HP6.

Two scales of the 3D model can be seen on a picture below.

Figure 12 3D printed locking bolt HP6 with 50% dimensions scale (left) next to model with 25% dimensions scale (right).

Printing head bolt HP3:

- Scale 50%,
- Printing time: 6h,
- 3D printer: Ultimaker 2+, nozzle 0.4,
- CAD software: NX – 3D part transport to STL,
- STL model treated for 3D printing in Cura Ultimaker software,
- Material: PLA, colour: blue,
- Nozzle: 0.40,
- Material: 10m.

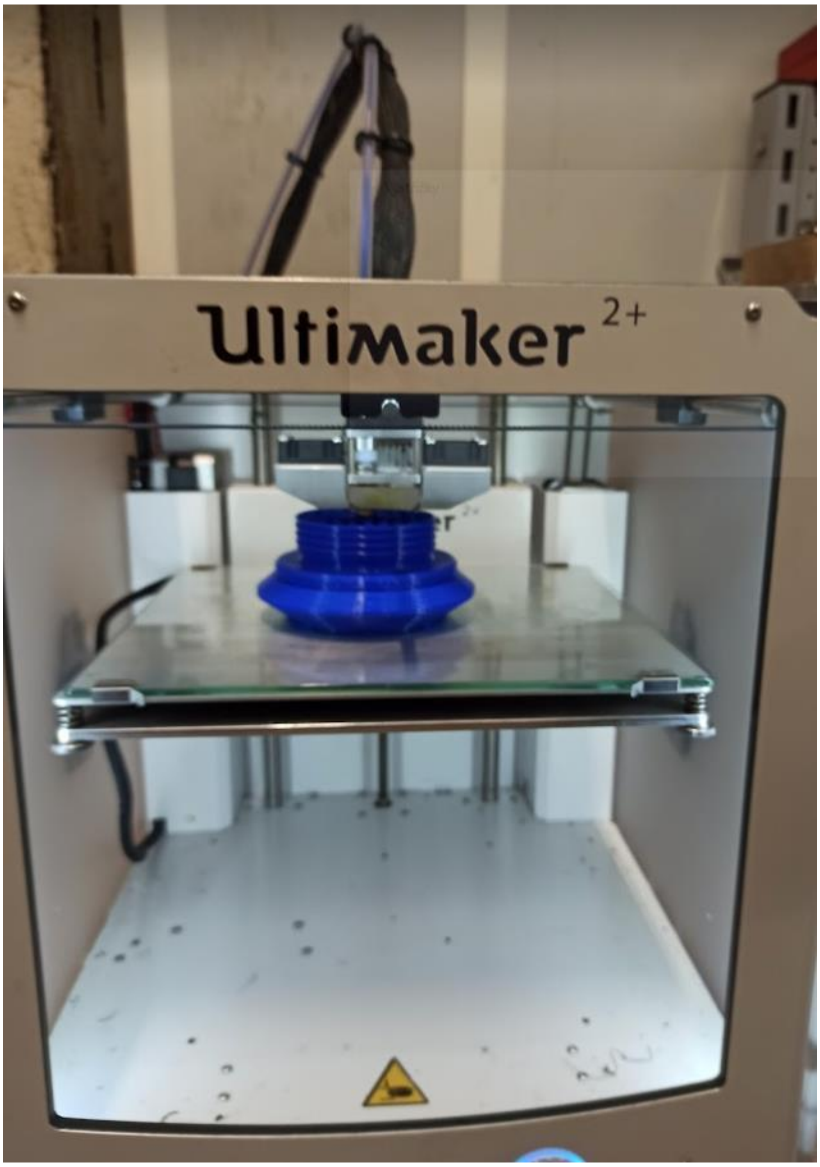


Figure 13 3D printing of locking bolt HP3 with 50% dimensions scale.

After the locking bolt 3D models were printed, it was necessary to eliminate supporting material.