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Influence of variable stress ratio during train operation on residual fatigue lifetime of railway axles

Pavel Pokorný[a,b,*], Luboš Náhlík[a], Pavel Hutař[a]

[a]dep. CEITEC IPM, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, v. v. i., Žižkova 22, 616 62 Brno, Czech Republic
[b]Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

Abstract

Railway axles are subjected to cyclic loading, which could lead to fatigue failure. Therefore, it is desired to know residual fatigue lifetime of railway axles to ensure safe operation of trains. Because of detection of relatively small fatigue cracks is not guaranteed an estimation of residual fatigue lifetime is based on damage tolerance approach. The acting stress ratio is variable due to variable amplitude loading and load caused by existence of press-fitted wheel in the vicinity of assumed crack. The contribution is focused on influence of variable stress ratio in EA4T steel on residual fatigue lifetime of railway axles. The influence of stress intensity factor on fatigue crack propagation rate was experimentally evaluated for three different stress ratios, which correspond to operation conditions. Two different expressions of fatigue crack propagation rate were used and mutually compared to show influence of the stress ratio on residual fatigue lifetime of structure made of EA4T steel. The first expression considers stress intensity factor range (respecting stress ratio R) and the second one uses maximal value of the stress intensity factor. The paper shows ability of both expressions to describe experimental data obtained under different stress ratios and their influence on estimated residual fatigue lifetime values. The results obtained contribute to the better estimation of residual fatigue lifetime of railway axles and generally to the safer rail transportation.

Keywords: railway axle; stress ratio, EA4T, fatigue crack

1. Introduction

It is a demand of customers and interest of producers to ensure reliability and safety of railway axles. Increasing demands require to involve damage tolerance approach to axle design process. This approach admits possibility that

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railway axle can include some defects incurred during manufacturing process or developed during train operation. The cyclic loading of railway axle (dominant is rotary bending due to weight and movement of the train) can lead to fatigue crack growth and consequently to fatigue failure of the railway axle.

The paper is focused on description of procedure for estimation of residual fatigue lifetime of railway axle, i.e. on determination of number of load cycles (or load blocks) for fatigue crack growth from initial defect (crack) to the critical one which leads to axle failure. The three dimensional numerical models were developed for determination of fracture parameters, see e.g. Pokorný et al. (2016). The fatigue crack was assumed and modelled at location where severity of loading is the highest. Such place is often at notch close to press-fitted wheel, see e.g. work of Zerbst et al. (2012). The notch represents a stress concentrator and existence of press-fitted wheel in its vicinity increases local stress concentration. The residual stress caused by press-fitted wheel represents mean stress in load cycle. The variability of axle load is described by representative load spectrum, see e.g. reference Traupe et al. (2004) or Pokorný et al. (2014). Fig. 1a shows typical load spectrum of railway axle with sorted load amplitudes into 36 load levels. The most of load amplitudes in this spectrum are concentrated near basic load level corresponding to rotary bending due to weight of the train. However, there are also rare load cycles with amplitudes circa 3 times higher than basic load.

The reliable procedure for residual fatigue lifetime estimation should contain the influence of residual stresses caused by existence of press-fitted wheel or developed during manufacturing process (e.g. hardening or surface deep rolling), see e.g. Hassani-Gangaraj et al. (2015). The total load is given by superposition of (bending) load amplitudes given by load spectrum and by residual stress component. The load stress ratio is generally different in each cycle, therefore suitable procedure should be used for residual fatigue lifetime estimation.

The fatigue crack was presumed at the notch close to press fitted wheel, see Fig. 1b. The fatigue crack front was considered as semi-elliptical with perpendicular orientation to railway axle axis. According to Schijve (2008) this assumption is based on fact that fatigue crack grows perpendicular to maximum principal stress and nearly perpendicular crack growth was observed during failure of real railway axles as well.

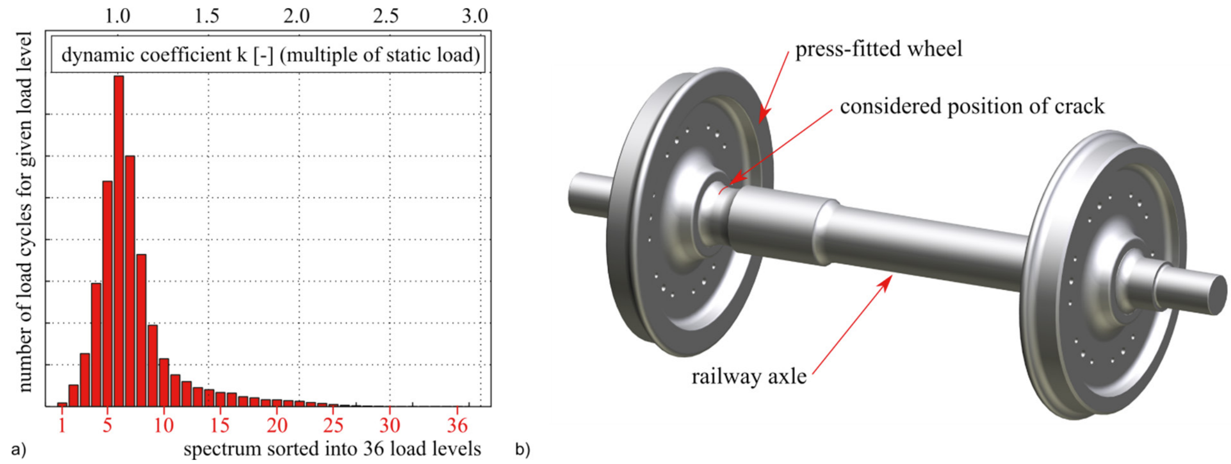

Fig. 1. (a) load spectrum - histogram expression; (b) scheme of wheelset with considered position of fatigue crack.

2. Effect of variable stress ratio R

The stress ratio R can be expressed as:

$$R = \frac{K_{I,\min}(a)}{K_{I,\max}(a)}, \tag{1}$$

where $K_{I,min}$ is minimal and $K_{I,max}$ maximal value of the stress intensity factor during load cycle.

Growing crack changes geometry of its crack front during propagation. Corresponding values of stress intensity factor can be determined analytically or numerically, however procedure of their determination is not aim of the paper, see e.g. Pokorný et al. (2016) for details. Fig. 2a shows stress intensity factor values of assessed axle as a function of fatigue crack length a. Both considered loads (bending and press-fit) contribute to opening of fatigue crack. The fatigue crack growth from 1 mm up to 55 mm was assumed in the presented study. The lower limit (1-2 mm) is frequently chosen due to detection limits of non-destructive testing methods. Fig. 2b shows typical dependence of fatigue crack length on number of applied cycles. It is evident that crack growth from 55 mm up to real critical crack length (with consequent failure) does not have significant contribution to total residual fatigue lifetime.

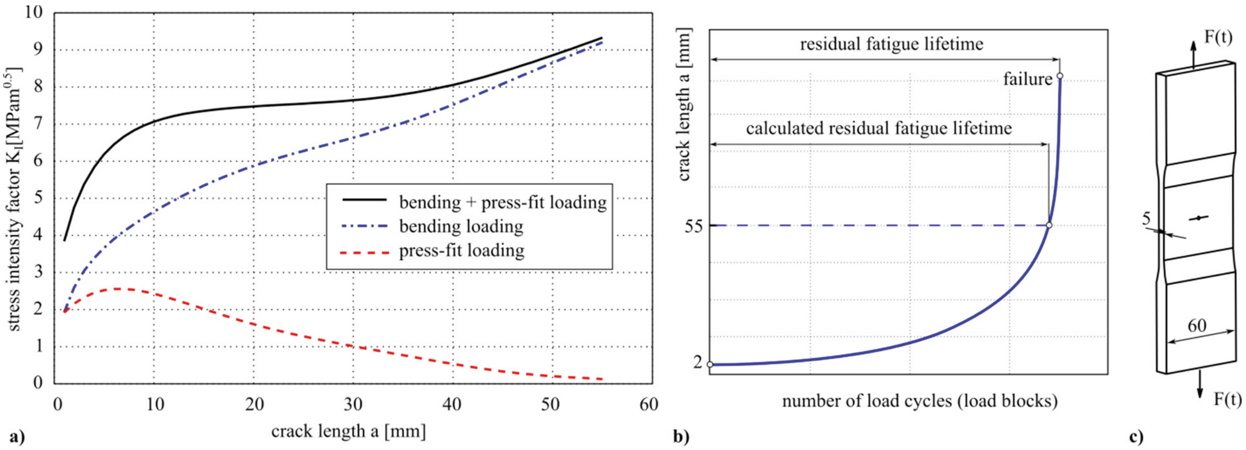

Fig. 2. (a) stress intensity factor values for bending load (caused by weight of train) and load caused by press-fitted wheel; (b) typical evolution of fatigue crack; (c) M(T) specimen used for determination of *v*-*K* curves.

The function belonging to bending loading shown in Fig. 2a corresponds to ride on straight track where dynamic effects are not present. This function describes stress intensity factors belonging to basic level of bending load. Nevertheless, the train also frequently goes to curve track, over switches, crossovers, etc. Mentioned events cause variable amplitude loading and enlarge “bending” load of railway axle. Load spectrum including these events is shown in Fig. 1a.

The maximal value of the stress intensity factor in general cycle can be expressed as:

$$K_{I,\max}(a) = K_{I,PF}(a) + kK_{I,B}(a), \tag{2}$$

and minimal value of the stress intensity factor in general cycle as:

$$K_{I,\min}(a) = K_{I,PF}(a) - kK_{I,B}(a), \tag{3}$$

where $K_{I,PF}$ is stress intensity factor caused by press-fitted wheel, $K_{I,B}$ is stress intensity factor caused by weight of the train (basic level of bending loading), k is the dynamic coefficient (representing multiple of basic “static” load) describing load spectrum according to Fig. 1a. The stress ratio can be then expressed as:

$$R = \frac{K_{I,PF}(a) - kK_{I,B}(a)}{K_{I,PF}(a) + kK_{I,B}(a)}. \tag{4}$$

Values of stress ratio R are calculated for all considered crack lengths according to relationship Eq. (4) and all considered load amplitudes from the load spectrum. Table 1 shows values of stress ratios R determined for crack length range from 1 to 55 mm and three dynamics coefficients ($k = 2.9$ - maximum value from the load spectrum, $k = 1$ - basic load level, $k = 0.9$ - minimum value from the load spectrum). It is evident from Table 1 that the stress ratio of railway axle varies during ride in the range from $R = 0.2$ to $R = -1$.

The residual fatigue lifetime is influenced mainly by the highest load amplitudes in load spectrum, which can induce stress intensity factor values higher than the threshold one, see reference Pokorný et al. (2015). The stress ratio of cycles with the highest stress amplitude (damaging amplitudes) is approximately $R = -0.5$ in the case of short initial cracks (1-2 mm). The effect of press-fit disappears in the case of longer cracks and the acting stress ratio is close to value -1.

Table 1. The various stress ratios R caused by variable amplitude loading and effect of press-fitted wheel.

crack length a [mm]	dynamic coefficient k		
	max. (k = 2.9)	mode (k = 1)	min. (k = 0.9)
1	-0.49	0.00	0.18
2	-0.55	-0.09	0.10
3	-0.58	-0.13	0.05
5	-0.61	-0.18	0.00
10	-0.69	-0.31	-0.14
20	-0.83	-0.57	-0.43
30	-0.90	-0.74	-0.64
55	-0.99	-0.97	-0.96

2.1. Experimental measurement of fatigue crack propagation rates

It is necessary for determination of residual fatigue lifetime to know dependency between the stress intensity factor K and fatigue crack propagation rate $v = da/dN$. Results in Table 1 were used during an arrangement of experimental measurements of v-K curves of EA4T steel. Three stress ratios ($R = -1$, -0.5 and 0.1) were chosen to determine the v-K dependence in the range of acting stress ratio of railway axle. For conservative estimation of residual fatigue lifetime it is worth to take into account v-K data, which were measured on specimen with lower in-plane constraint factor than the railway axle exhibits. This requirement is fulfilled by use of M(T) specimen, see Fig. 2c.

The tests were performed in the frame of research infrastructure IPMinfra using resonant machine SCHENCK with mean force range ± 30 kN and maximal load amplitude 30 kN. The testing frequency was in range from 60 Hz to 40 Hz in dependence on crack length. The fatigue cracks were initiated from sharp notches (two sides), which were manufactured by electro discharge method. Fatigue crack propagation rates were measured according to ASTM E647 after crack initiation. The crack length increments were measured optically on both sides of M(T) specimen by using of CCD cameras uEye UI-2280SE-M-GL with lenses Lensagon CMFA2520ND. The positions of cameras were tied with digital indicators Sylvac CO MFPM 25 with accuracy 0.01 mm. Fourteen specimens were used (five specimens for stress ratio $R = -1$, five for stress ratio $R = -0.5$ and four for ratio $R = 0.1$) for determination of v-K data. Obtained experimental data are shown in Fig. 3a.

The threshold value of stress intensity factor is of crucial importance in considered kind of application, therefore this value was evaluated from experimental data and compared with formerly published data. The Fig. 3b shows measured threshold values ΔK_{th} in dependence on stress ratio R, where data published by Regazzi et al. (2014) and Varfolomeev et al. (2011) are plotted for comparison. Fig. 3c shows comparison of maximal values $K_{th,max}$ with respect to stress ratio calculated from following relationship:

$$K_{th,\max} = \frac{\Delta K_{th}}{1-R}. \tag{5}$$

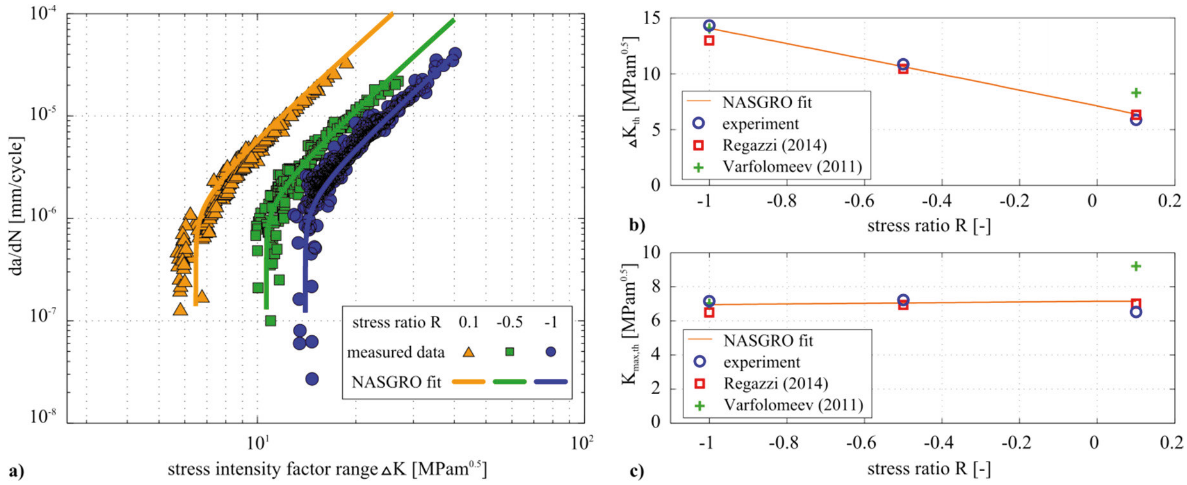

Fig. 3. (a) Measured *v-K* data (*R* ratios were considered: -1; -0.5; -1); (b) The dependence of threshold value ΔK_{th} on stress ratio *R*; (c) The dependence of threshold value $K_{th,max}$ on stress ratio *R*.

2.2. Fatigue crack propagation rate description

Very common approach NASGRO [NASGRO manual (2002)] was chosen for the interpolation of experimental data:

$$\frac{da}{dN} \approx \frac{\Delta a}{\Delta N} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_c}\right)^q}, \tag{6}$$

where C, n are material constants and p, q empirical constants describing the curvatures that occur near the threshold and near the instability region of the crack growth curve, respectively and f is crack opening function. The residual fatigue lifetime is dominantly given by propagation rate of relatively small crack in the studied case, see Fig. 2b, therefore the denominator $(1-K_{max}/K_c)^q$ (corresponding to rapid propagation of longer cracks) can be neglected. Then the NASGRO can be expressed in the form:

$$\frac{da}{dN} \approx \frac{\Delta a}{\Delta N} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p . \tag{7}$$

Note that Eq. (7) was used for fit of material data in Fig. 3a.

The stress intensity factor range is function of the crack length *a,* therefore:

$$\Delta K(a) = K_{I,\max}(a) - K_{I,\min}(a) = 2kK_{I,B}(a) . \tag{8}$$

The effective stress intensity factor range considers different crack closure under different *R* ratios:

$$\Delta K_{eff} = \left(\frac{1-f}{1-R}\right)\Delta K . \tag{9}$$

The opening function *f* is defined by Newman empirical description:

$$f = A_0 + A_1 R \ , \qquad -2 \le R < 0 \tag{10}$$

$$f = \max(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3) , \qquad R \ge 0 \tag{11}$$

where A_0, A_1, A_2 and A_3 are polynomial coefficients of Newman's crack opening function:

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2)\left[\cos\left(\frac{\pi}{2}\sigma_{\max}/\sigma_0\right)\right]^{\frac{1}{\alpha}}, \tag{12}$$

$$A_1 = (0{,}415 - 0{,}071\alpha)\sigma_{\max}/\sigma_0, \tag{13}$$

$$A_3 = 2A_0 - A_1 - 1, \tag{14}$$

$$A_2 = 1 - A_0 - A_1 - A_3, \tag{15}$$

where α is constraint factor. It is considered in calculations that plane strain prevails and α = 3. The parameter σ_{max} is maximum applied stress and σ_0 is flow stress. The flow stress was taken as average value of yield and ultimate strength according to reference NASGRO manual (2002). Herein considered σ_0 = 600 MPa.

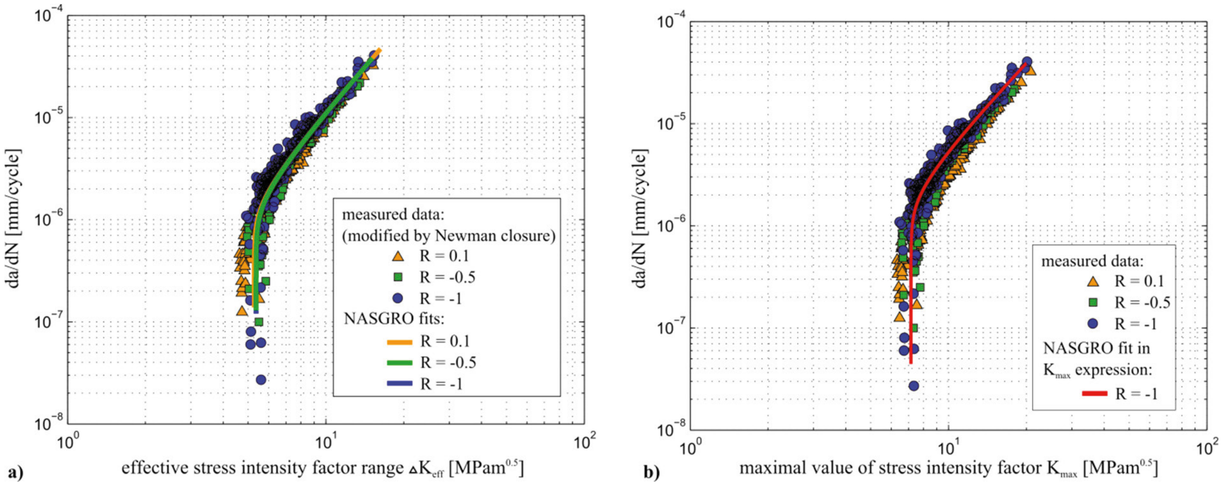

Fig. 4. The dependence of crack propagation rate $v = da/dN$ on (a) effective stress intensity factor range, (b) maximal value of stress intensity factor

The Fig. 4a shows measured data where horizontal axis is transformed into effective stress intensity factor range by considering Eq. (9). This transformation leads to effect that v-ΔK_{eff} curves obtained under different stress ratios fit quite well each other. However, the slightly difference between data obtained for different R in threshold area occurs. The NASGRO fit of threshold data is determined according to procedure described in NASGRO manual (2002). The result of this threshold value fit is evident in Fig. 3b. Based on measured data the empirical fit of threshold values is given by parameters $C_{thp} = 2.056$, $C_{thm} = 0$ and $\Delta K_1 = 2.94$ MPam$^{0.5}$, see reference NASGRO manual (2002) for detail description of these parameters.

The Fig. 4b shows dependence of fatigue crack propagation rate $v = da/dN$ on maximal value of stress intensity factor K_{max}. The measured data fit each other pretty well in v-K_{max} expression for different stress ratios R in considered range from -1 to 0.1. It means that fatigue crack propagation rate for particular maximal value of the stress intensity factor K_{max} is almost the same for stress ratio $R = -1$ and $R = 0.1$. It follows that for the description of fatigue crack propagation in EA4T steel and operation stress ratio range (from $R = -1$ to $R = 0.1$) just one v-K_{max} dependence is sufficient. The measured data exhibits slightly higher propagation rates in linear region of v-K_{max} dependence for stress ratio $R = -1$, see Fig. 4b. Therefore, data determined for stress ratio $R = -1$ are used in Eq. (16) for conservative determination of residual fatigue lifetime of railway axle. The description of v-K_{max} dependence is provided by modification of NASGRO model according to Eq. (7):

$$\frac{da}{dN} \approx \frac{\Delta a}{\Delta N} = C^*\left[K_{I,\max}\right]^{n^*}\left(1 - \frac{K_{\max,th}}{K_{I,\max}}\right)^{p^*}. \tag{16}$$

As was mentioned formerly, such description is slightly conservative for $R = -1$ and simpler than original NASGRO relationship. The material constants C^*, n^* and p^* have the same meaning as C, n and p, but their values are different in general. The threshold value $K_{max,th}$ was taken as a constant in relationship (16) according to results depicted in Fig. 3c. Note that $K_{\max}$ approach for crack propagation rate description under negative R was formerly used e.g. in Vasudevan and Sadananda (1999).

2.3. Estimation of residual fatigue lifetime

The load spectrum is described by load block in the procedure of estimation of residual fatigue lifetime. The load block represents specific amount of kilometers during axle operation. The fatigue crack increments are calculated for all load levels contained in load spectrum. Calculation runs in a loop until length of fatigue crack does not overcome the considered critical length $a_c = 55$ mm. The crack increments Δa were determined by using of discretized forms of relationships (7) and (16):

$$\Delta a = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p \Delta N \quad \text{and} \quad \Delta a = C^*\left[K_{I,\max}\right]^{n^*}\left(1-\frac{K_{\max,th}}{K_{I,\max}}\right)^{p^*} \Delta N \text{ respectively.} \qquad (17)$$

The crack increment Δa equals to zero until the stress intensity factor range or maximal value of stress intensity factor does not overcome the threshold value ΔK_{th} or $K_{th,max}$ respectively.

2.4. Results and discussion

Two above mentioned procedures were used for lifetime estimations. The relationship (7) considers as inputs applied stress intensity factor range, stress ratio and also analytically determined function of crack closure. The approach expressed by Eq. (16) uses maximal values of the stress intensity factor for lifetime estimation. It should be emphasized that both approaches consider effect of press-fitted wheel. The press-fit effect in Eq. (16) is included according to Eq. (2), i.e. by increase of stress intensity factor values.

Table 2. Estimated residual fatigue lifetimes of railway axle (in load blocks) for different initial crack lengths.

	initial crack length a_0 [mm]				
	1	1.5	2	3	5
according to v-ΔK (Eq. (7))	12 344	420	192	121	84
according to v-$K_{\max}$ (Eq. (16))	16 001	380	159	100	69

The Table 2 shows estimated residual fatigue lifetimes obtained by both above described approaches. The results are very sensitive to threshold value, because only peak amplitudes from the applied load spectrum exceed the threshold value. This is valid mainly for short cracks. Both approaches provide similar results. It is possible to declare that on the base of measured data the NASGRO approach expressed by Eq. (7) slightly better describes the crack propagation rate for different R in the mid-region of v-K curve. It is due to better description of plasticity induced crack closure in this region. The approach based on Eq. (16) is slightly conservative from this point of view. However, it is difficult to decide what description is better in the threshold region, where description by analytical interpolation function contains its limitations as well as the general validity of the fact that threshold values are constant for negative R, even though some works proved that idea, see e.g. Vasudevan and Sadananda (1999). It is necessary to notice that K_{max} approach is suitable only for stress ratio range negative or slightly positive (close to zero). This approach is unsuitable for application with important positive R, where the crack closure plays different role than in the case of low or negative R. The advantage of K_{max} approach for application on railway axle can be found in decrease of necessary experimental measurements (v-K curve only for the lowest applied R is needed) and simpler procedure of determination of residual fatigue lifetime. The results obtained are valid for considered EA4T steel. Its generality will be validated in future for other steels of the same class.

3. Conclusion

For reliable estimation of residual fatigue lifetime of railway axles the effect of the variable stress ratio R should be determined. The EA4T steel was chosen as etalon of railway axle material for this investigation and its v-K dependence was experimentally measured for different R values. Two different approaches were used for evaluation of measured data. First was based on NASGRO approach published by Newman and the second one was based on use of only positive part of load cycle (K_{max}). It was shown that for given application and material both approaches provides comparable results. It is evident that sophisticated NASGRO approach is more general and can be used in many application for determination of crack growth under different conditions, but the time and costs for determination of all necessary parameters can be quite high in this case (NASGRO requires at least two v-K dependence measured on different stress ratio to evaluate crack closure effects). Presented K_{max} approach is valid only for low or negative R, however only v-K curve for the lowest applied stress ratio (R = -1 was used in studied case) is necessary for its use. The future work will be focused on proof of generality of this conclusion at least for the materials suitable for railway axles. The proof of validity of this approach can lead to the faster use of new or modified axle materials or can decrease the costs of experimental determination of material characteristics.

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