PARAMETARS OF LIMIT CONDITIONS OF RAILWAY CONSTRUCTION ELEMENTS WITH CRACK

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Summary

Physical exertion parameters of material conditions of railway vehicle construction elements with registered defect in service are bases for accurate evaluation of the destruction process and strength loss from fracture mechanics viewpoint. Limiting conditions of elements with crack are function of loading style, temperature, plastic deformation character, load condition in the growth zone and crack growth law, crack sensibility of material, crystal lattice characteristics, corrosion stress and corrosion fatigue etc. Prognosis of residual lifetime from fracture mechanics viewpoint, by making relation for determining the generalized force value which indicates spreading of the crack to the limit length which result will be structural loss, is made. The purpose of this article is analysis of the limit conditions of railway construction elements with crack, plastic deformation character and destruction development and parameter value definition relevant for residual lifetime calculation from fracture mechanics viewpoint, and for diagnostic objectivity growth, needed steps for holding of construction integrity.

1. INTRODUCTION

Railway vehicles structure elements are submitted, at first, to high static stress due to dimension differences and residual welding stresses. Cycle stress components during railway vehicle running on track (steel to steel) are mechanically transmitted. Vibrations of compressor connection equipment, traction motors, brake systems, buffing and coupling gears, temperature cycling etc. are added here. Fatigue process starts from stress concentrators, like discontinuities and cuts, which provoke triple axes stress condition in material. Progressive development of a crack or more cracks at the moment when residual section loses ability to respond to a load brings to fatigue fracture, because of action of cycle changeable operational stresses. At the first approximation, from the aspect of fracture mechanics, general algorithm for prognosis of element endurance with registered damage in high cycle fatigue area can be approximated in operational process as follows:

1. Choice of relation, which describes stress condition – accumulated stress concentration (K) in crack zone as a function of cycle stress level and character, material quality, element configuration, crack location and shape $l: K = C \cdot \sigma \sqrt{l}$;

2. Adoption of relation that describes crack length change, like Paris-Erdogan relation $l = \alpha \cdot K^n$, from crack length that can be identified by NDI methods, as a function of accumulated stress concentration and cyclic material resistance parameters α and n;

3. Adoption of a relation for crack growth speed on stress cycles (fatigue damage accumulation speed) for range ΔK: $dl/dN = \alpha \cdot \Delta K^n$ i.e. $dl/dN = \beta \cdot \sigma^n \sqrt{l}$, where is: $\beta = \alpha \cdot C^n$ and $C = \sqrt{\pi/2}$;

4. Creating a relation for generalized J integral ($J_{(l/l_0)} \neq 0$), by relation integration dl/dN within limits from 1 to l/l_0 1;

5. Duration prognosis expressed in number of stress cycles from momentary (crack NDI) to critical length *l*cr (results fracture), by application of integral value J;

6. Prognosis *l*cr for preferable duration N for the purpose of maintenance defining (reflexive information σ_d for given dl/dN on the basis of K_{Ic});

7. Duration prognosis for prognostic reduction grade σ_d so that existing crack ($l*$) doesn't grow further;

8. For prognosis of residual life from simultaneous influence of corrosive stress and corrosion due to fatigue, instead of relation that describes momentary crack length, the relation for damage accumulation during time should be used:
$\nu_{tscc} = J_m / 2 \cdot \alpha_0 \, N_0 \cdot t_0$, where are: J_m $(J_4, J_6, J_8 \text{ and} J_{10})$ – values of accumulated force that provokes crack spreading for material endurance curve parameters m = (4, 6, 8 or 10); α_0-parameter nominal value for function which presents reduction of material endurance limit $\alpha(\sigma)$ and t_0-mean value of acting time for operational stress.

The problem is that fatigue doesn't submit under up to date criterion of limit states, taking into

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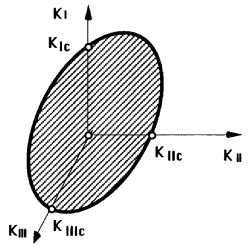
consideration that allowed fatigue strength in the area of engineering construction submitted to variable strains, is lower from limit state. At high cyclic fatigue is far lower. And at low cyclic slightly lower, but in the domain of plastic deformation. At endurance prognosis for problem solution it is necessary to analyze changes in elements with damage which causes limit states.

2. LIMIT STATE CAUSES IN ELEMENTS WITH CRACK

Changes in elements with crack that because limit states in theirs first approximation are defined by: stress state in crack growth zone and growth law, material strength – sensitiveness to cracks, material crystal lattice characteristics, corrosive stress and corrosive fatigue.

To stress state objectivity, in the crack growth zone, can be contributed by inputting influences of material nonlinear deformability effects, adjustment to sharp cracks, punctuality of influence of the plastic deformation spreading zone etc. General condition of material destruction (1) with existing damage with limited size, for the general load case in conditions of flat deformation, defines values for allowed stress concentration strength round the crack tip, i.e. the elliptic surface of limited crack fracture toughness (fig.). Strength measures for stress singularity for the all deformation shapes (according to Griffith: an energy to crack surface unit, necessary for formation of the new fracture surface behind the crack tip), are limited by the surface of limit fracture toughness of a crack.



$$\left(\frac{K_I}{K_{Ic}}\right)^2 + \left(\frac{K_{II}}{K_{IIc}}\right)^2 + \left(\frac{K_{III}}{K_{IIIc}}\right)^2 = 1 \quad (1)$$

Fig. Material deterioration elliptic surface

a) Evaluation for resistance to fracture at the condition of non destruction, is directly defined from the general destruction condition (1): for quasi-clean tearing in the conditions of flat deformation $K_I \le K_{Ic}$, or $K_I \le K_c$; in conditions of stress flat state; and analogously; for quasi-clean sliding in a plain, $K_{II} \le K_{IIc}$; and for quasi-clean share, $K_{III} \le K_{IIIc}$.

b) Direction of possible destruction from the condition (1) can be determined with previous definition about basic laws for influence of main causes to crack growth and they are:

- stress trajectory in plastic zone and its expected maximum for the condition that the crack growth direction is normal to the direction of maximum normal stresses action.
- Shape of plastic zone by application of plastic criteria: -maximum tangential stresses or limit energy criterion for shape change.

It is emphasised that with larger element thickness, under the state conditions when plastic and stress zones have flat deformation, stress concentration rapidly grows in plastic zone (round circle opening $\sigma_y = 3\sigma_T$, and plastic zone diameter is even 9 times smaller).

Material sensitiveness to cracks can be easily defined through factors that control fracture due to fatigue: level of acting σ_d stress, critical crack length l_{cr}, fracture toughness at flat deformation K_{Ic}, and influence of local residual stresses, temperature, parameter values as a function of material fracture toughness with the flat deformation etc.

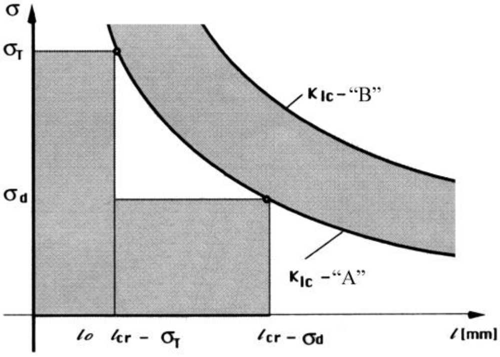
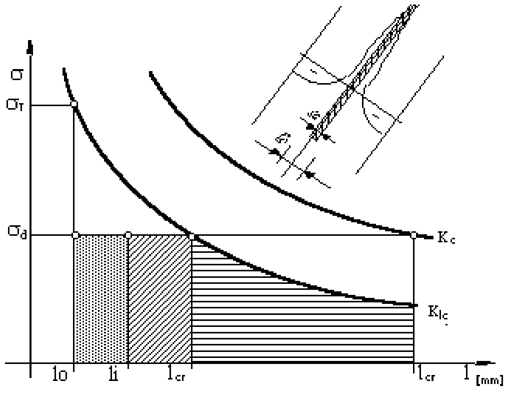


Fig.2. Material quality effect to fracture



changing from KIc to Kc

Fig.3. Influence of local residual stresses near weld

Figure 2 shows an effect when applying material with higher strength values against fracture "B". Actual stress can be equalized with achieved stress on small range, in ranges of high residual stresses, so l_{cr} should be defined for σ_T instead for σ_d, ($l_0 = l_{cr}$). When both, basic metal and welded metal, are strong enough (for instance material "B" fig.2), l_{cr} is also satisfactory for totally achieved load. At loading with material fatigue, taking into consideration that the crack can grow outside a zone of residual stress, l_{cr} should be defined on the level of σ_d, because it is not material constant, but σ_d, function. This doesn't apply to state structures with initial load – (monocle wheels), i.e. crack dullness caused by high residual stresses.

Materials with low values of K_{Ic} can be applied in cases with decrease of σ_d during strain; action of preventing crack initiation; stress rearrangement that causes initiation, growth and the crack is directed to reduction stress area, or it is not oriented towards critical plain of unstable spread cause (case of “scaling” on rails). Figure 3 shows an influence effect from local residual stresses on to fatigue crack increase and also shows an effect of conditions caused by flat deformation and flat stress state crack “loss” due to local weakening of material strength in residual tension ranges. Never the less that in period of following stresses, regions close to weld can hardly show elastic behaviour as a response to stress, there shouldn’t be early damage, because plastic behaviour relies on redistribution of local stress concentration. Definition l_{cr} for σ_d and material thickness analysis is required here. For high values of l_{cr}, sub critical growth of fatigue crack is a cause for stress weakening, which results in stress in plane or elastic-plastic behaviour. Determined l_{cr} is by accomplished stress at elements where appearance of cracks is expected, and than l_{cr} is compared to maximum possible value from the basis of possible technology of manufacture and inspection. For high strength materials any crack that appears should be hold rapidly, so it doesn’t leave high residual stress range (l_0 fig.3.). The effect is small at crack fatigue growth.

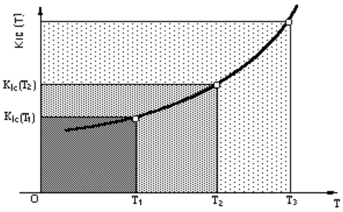


Fig. 4. Temperature influence on fracture toughness

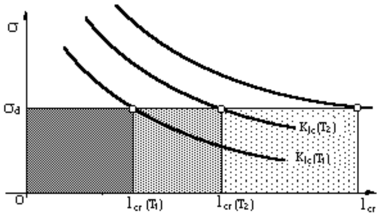


Fig. 5. Decrease of fatigue crack critical length l_{cr} with temperature decrease

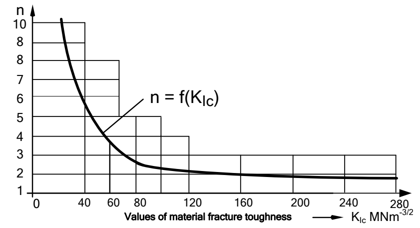


Fig. 6. Curve for exponent values n = f(KIc)

Figure 4 shows influence the temperature on strength in conditions of flat deformation $K_{Ic}(T_i)$. Figure 5 shows the effect of l_{cr} decrease for the same level of σ_d with decrease of K_{Ic} at the temperature decrease. Figure 6 shows the change of parameter n in equation Paris-Erdogan $dl/dN = \alpha \cdot \Delta K^n$ for different values K_{Ic} for material steel with mean and high strength. Figure 6 shows $n > 3$ for $K_{Ic} < 60\ MNm^{-3/2}$ and $n = 2 \div 4$ for elastic-plastic behaviour.

Material crystal lattice is characterized on the basis of influence to strength and metallurgical influence – when non-metal inclusions act as deformation centre and reduce the initiation period of cracks due to fatigue, location of structural an-homogeneity is a crack start. That can cause fatigue or brittle fracture in the latest stadium.

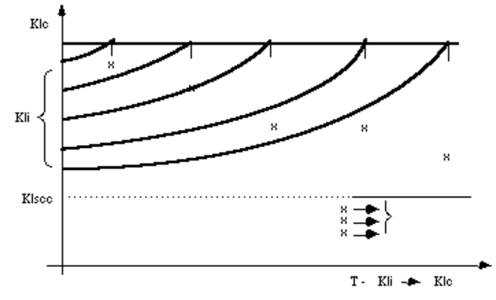


Fig.7. Fracture strength changes KIc to Kiscc (x-tests without appearance of crack growth)

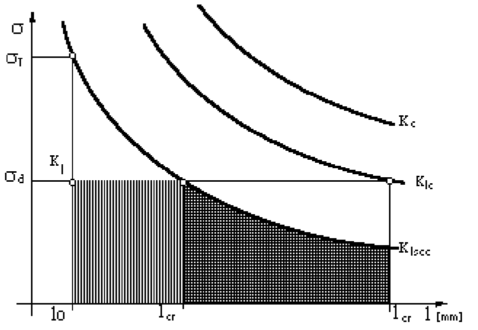


Fig.8. Crack increase l_o to l_{cr} from fatigue influence or corrosive influence and from corrosive stress influence

Presence of impurities in the shape of rough bubbles brings to creation of closed “islands”, disturbs integrity, reduces carbon contents, which causes ferrite structure and strength reduction. Hydrogen “flakes” are consequence of cracking of closed hydrogen islands in steel during cooling, which reduces creation period of fatigue cracks. Smaller longitudinal hydrogen flakes (on tracks) are more common during slower cooling, but during fast cooling, piles of longitudinal and transversal hydrogen flakes are created. Nitrogen, during aging of unstable steels, partly changes carbon in carbides and increases influence of intramural phases (sigma and Laves), which bring to fracture. Piles of carbon atoms round dislocations and presence of nitrogen and water carbon nitrides lead to steel hardening and brittle incensement. An-homogenises in contents of P, S, C, O, H oxides, accumulated sulphides, nitrides, carbonizes etc. in the shape of parallel surfaces arranged by high, bring to appearance of woody crack. Annealing only covers with marten sit structure. On working temperature 200°C and higher, marthensit decomposes, plastic state increases and woody appears again due to temperature decrease. At welded ferrite steels, from fracture mechanics viewpoint, dependence of crack growth speed as tearing is significant - $dl/dN$with change of ranges ΔK. Despite the difference in chemical composition, microstructure and mechanical characteristics, tested steels $\sigma_T = 400 \div 1300 Mpa$ have almost same strength ($400 dl/dN = 10^{-1} \div 10^{-3}$) to crack spreading – described by relation: $dl/dN = 5 \cdot 108 \cdot \Delta K^{-2,7}$.

Crack growth under conditions of corrosive stress is extremely difficult to predict under the presence of variables like chemistry, temperature, corroding concentration at the crack tip etc. Real approach of constant danger from destruction is application of constant support for reached level K_{Iscc} as limiting curve (fig.7.). Approach defines “damage” as crack growth initialization under corrosive stress conditions. Crack is only function of time until the level of component K_I round crack tip reaches the value K_{Ic}, which brings to total destruction and is considered as critical, because cycle number of corrosive stress can not be estimated. Surrounding factors: chemical, corrosion, corrosive stress, cavitations, production quality etc. are the main for appearance and the basis for critical crack length prognosis, and significant for operational material behaviour (fig.8.).

3. CONCLUSION

By performed analysis of limit condition causes, all in purpose for duration definition accuracy and fracture control interval (manufacture design) it is suggested:

- For ultra hard steels with$K_{Ic} > 0,5 \cdot \sigma_{02}$, as the main cause of limit state take corrosive area condition on crack length - relation: $l = 0,2 \cdot (K_{Ic} / \sigma_{02})^2$.
- For practical, apply experimental equation as a function of cyclic characteristics of fracture toughness:

$$dl/dN = \begin{Bmatrix} (0, & za\ 0 \le K \le Kth) \\ \alpha \cdot \Delta K^n, & za Kth \le K \le Kfc \\ \infty, & za\ K \succ Kfc \end{Bmatrix}$$

and apply empiric dependence between cyclic K_{fc} and static fracture toughness K_c (K_{Ic}): $K_{fc} = (0,5 \div 0,6) K_c$, (instead of K_{fc} for crack growth speed $3 \div 4 \cdot 10^{-3}$ mm/cycle and K_{th} for $3 \div 4 \cdot 10^{-7}$ mm/cycle).

Parameters of cyclic material strength to fatigue cracks α and n and cyclic toughness of the beginning of crack controlled growth K_{th} determine according to correlative empiric equations connected to σ_{02} and σ_V expressed in N/m^2: $\log\alpha = 0,056\sigma_V - 13,72$ and $n = 4,52 - 0,0026 \cdot \sigma_{02}$; $Kth = 12,7 - 0,006 \cdot \sigma_{02}$ $[N/m^{3/2}]$; all in function of cycle asymmetry: $K_{th,R} = K_{th,0} - (11,37 - 0,0065 \cdot \sigma_{02})$ $[N/m^{3/2}]$ for $R = 0 \div 0,9$. For marthensit and nickels steels values are satisfactory for $K_c = 230 N/m^{3/2}$ and $K_{Ic} = 95 N/m^{3/2}$; for carbon steels $K_c = 64 N/m^{3/2}$ and $K_{Ic} = 32 N/m^{3/2}$. In relation $dl/dN = \alpha \cdot \Delta K^n$ for elastic-plastic material behaviour, values are satisfactory for$n = 2 \div 4$. For thermal cracks created during braking $\alpha \approx 0,5$ and$n \approx 2,45$. For welded ferrite steels apply relation $dl/dN = 5 \cdot \Delta K^{-2,7}$.

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