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Igor VAKULENKO[1], Svetlana PROYDAK[2], Hangardas ASKEROV[3]

THE CALCULATION OF STRESS INTENSITY FACTOR STEEL OF RAILWAY WHEELS

Summary. From an analysis of the dependence complex of carbon steel properties on structural parameters, it was found that for an isostructural state, the influence of austenite grain size on impact strength exceeds the dependence on carbon content. As a result of explaining correlation relationships between individual mechanical characteristics, to evaluate critical stress intensity factor, a relationship is proposed based on the use of impact strength. The proportionality coefficient in proposed dependence is determined by ratio of elongation to narrowing at tensile test.

Keywords: stress intensity factor, impact strength, elongation, narrowing, austenite, pearlite

1. INTRODUCTION

During operation of railway transport, elements railway wheels are exposed to complex total stresses [14,16,17]. Achievement maximum permissible concentration defects of crystalline structure in metal of wheels determine the conditions for the formation and growth

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[1] Dniprovsk National University of Railway Transport Named Academician V.Lazaryan, Lazaryan St.,2, Dnipro, Ukraine, 49010. Email: vakulenko_ihor@ukr.net. ORCID: https://orcid.org/0000-0002-7353-1916
[2] Dniprovsk National University of Railway Transport Named Academician V.Lazaryan, Lazaryan St.,2, Dnipro, Ukraine, 49010. Email: proydak.sv@ukr.net. ORCID: https://orcid.org/0000-0003-2439-3657
[3] Mechanical Engineering, Karabuk University, Karabük, Turkey. Email: hangardasaskerov@karabuk.edu.tr. ORCID: https://orcid.org/0000-0003-4771-3406

of fracture centres [18]. In addition, dispersion and morphology of phase components that determine the level of strength properties, reliability operation of the wheels largely depends on the sensitivity of metal to stress concentrators from micro- and macro- mechanical damage rolling surface, cracks various origin [6], etc. Of the many characteristics, certain propagation was obtained by the stress intensity factor at beginning of interval unstable crack growth (K_{1c}) [15]. The specified characteristic determines the condition for the formation of a plane-deformed state of metal at the mouth of the crack. According to the results of numerous studies [3,13,19], use K_{1c} allows us to estimate the maximum allowable stress at which there is no growth formed crack a certain size. Similarly, ambiguity of the dependence K_{1c} on certain structural components of carbon steel [7] and the static conditions for its determination can distort the nature of its change. This situation is due to absence of considering explicit effect shock pulse of the load when K_{1c} determining, although, during operation, the railway wheels are subjected to numerous dynamic influences. On the other hand, the search for K_{1c} correlations with other fracture toughness characteristics may be the basis for the development of a comprehensive parameter that considers larger number factors determining the metal resistance to fracture.

2. MATERIALS AND METHODS

The material used for this study was carbon steels of railway wheels with different contents of chemical elements: 0,47% C, 0,71% Mn, 0,3% Si, 0,015% P, 0,012% S (St. A); 0,55% C, 0,64% Mn, 0,34% Si, 0,014% P, 0,009% S (St. B); 0,59% C, 0,81% Mn, 0,3% Si, 0,019% P, 0,017% S (St. C); 0,63% C, 0,72% Mn, 0,29% Si, 0,017% P, 0,02% S (St. D); 0,65% C, 00,73% Mn, 0,31% Si, 0,017% P, 0,009% S (St. E). The blanks of samples for tests on static tension, determination of K_{1c}, impact strength (*KCU*) and fatigue were processed to obtain different austenite grain sizes (*d*) using heating and holding at temperatures above A_{C3}. The thickness ferrite layer of perlite colonies was regulated by changing the temperature of isothermal transformation austenite at pearlite region on thermo kinetic diagram. The yield stress (σ_y), stress strengths (σ_s), and plastic properties (elongation -δ and narrowing -ψ) were determined from analysis of tensile diagrams obtained at a temperature of $+20^{\circ}C$ and a strain rate of $10^{-3}s^{-1}$. Values K_{1c} and *KCU* were determined according to known methodologies [5,13]. The microstructure was examined under a light and electron microscopes. The austenite grain size and thickness ferrite layer of perlite colony (λ) were estimated in accordance with methods of quantitative metallographic [2].

3. RESULTS AND DISCUSSION

Based on studies [9], it was found that regardless of nature loading metal material, the fracture process consists of several successively developing stages: from moment formation lesion focus, its growth up to final destruction of the metal. Assuming that process, micro crack nucleation to a certain extent is determined by ability metal to strain hardening [11], under conditions of static loading, the differences dependences of strength and plastic properties on size of structural element are completely justified. For carbon steel, of rim railway wheel dispersion of perlite colony is the main structural parameter. The ability of perlite to deform as a whole [1], restriction of dislocation reactions to the thickness of ferrite gap of a pearlite colony, and parabolic nature of hardening from λ [1,10,11] are determined by the relations

$\sigma_Y, \sigma_S, \delta, \psi \approx f(\lambda^{-0,5})$ (Fig. 1). Low degree accumulation of dislocations during loaded steel up to level of yield stress explains the absence of explicit influence volume fraction of cementite *(f)* (Fig.1a). A similar explanation, at case of slight change in *f*, albeit with certain reservations, can be propagated and for fatigue limit (σ_{-1}) (Fig.1b). The value of σ_s, to a greater extent, in comparison with σ_y, depends on *f*. If the level σ_s is largely determined by development of processes strain and dispersion hardening [10], then plasticity characteristics should apparently be related to compatibility of propagated deformation in phase components of steel [11]. Indeed, the plasticity level of steel, on the one hand, is limited by ability, a cementite of pearlite colony endure certain plastic deformations [1], on the other hand, is determined by the higher ductility of structurally free ferrite. Thus, compatibility conditions at propagation plastic flow in pearlite colonies and in areas of structurally free ferrite can be characterised by δ and ψ. However, after stress reaches the level σ_s and the corresponding plastic deformation, exhaustion of accumulation resource of defects crystal structure in any of phase components carbon steel will be the beginning of a complex fracture process. Starting from moment of crack initiation, critical growth conditions at various stages are estimated by the stress intensity factor at mouth of crack [3,13,19]. The dependence K_{1c} on the thickness of ferrite gap pearlite colony (Fig.1b) is similar σ_y (Fig.1a), for same interval of variation volume fraction of cementite. Thus, an increase dispersion of pearlite at same carbon content is one of the main directions of increase K_{1c} for steel railway wheels. Meanwhile, the discovered evidence of deviations from indicated nature of K_{1c} change indicates the need to consider additional influence factors. Indeed, for the carbon steel of railway wheel, in addition to pearlite colony dispersion, the state of austenite grain boundaries has a definite effect on the crack resistance of the metal [4]. It is known that with constant content atoms of harmful impurities in steel, at increase in *d* thereby increases their concentration at grain boundaries, contributing to the transition of metal to a brittle state, especially under conditions of impact loading. The nature effect of *d* on K_{1c} and σ_{-1} of studied steels is given in Fig. 2. In contrast to K_{1c} and σ_{-1}, impact strength, being a rather sensitive characteristic for evaluation state of grain boundaries austenite of carbon steel [1,4], is used in regulatory documents as a parameter for the quality of railway wheels for various purposes. Effect of *d* on *KCU* is shown in Fig. 2c. The practically absent effect of carbon content in steel can be considered as evidence of a certain sensitivity, this characteristic to concentration of harmful impurities at austenite grain boundaries. In general, the stress intensity factor is estimated by the dependence [6,15]:

$$K_{1c}^{\ 2} = E \cdot G, \tag{1}$$

where *E* - is Young's modulus, *G* is the energy of deformed metal. When the formed of volumetric stress state, the required energy at growth unit surface of the crack does not exceed absorbed energy by metal, the relation [8] is satisfied:

$$G = \frac{\pi \cdot \sigma^2 \cdot l}{E}, \tag{2}$$

where *l* - is half length of crack. After substituting (2) in (1), obtain dependence for determining stress intensity factor under static loading:

$$K_{1c} = \sigma \sqrt{\pi \cdot l} \tag{3}$$

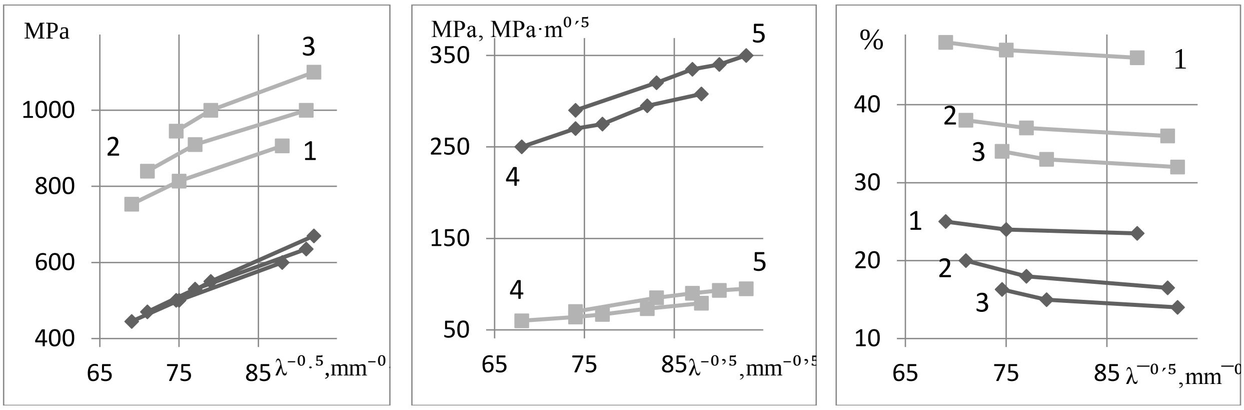
Existing difficulties in the interpretation [3,15] and definition of G [8,12] indicate the need to search for another parameter to determine K_{1c}. Considering that value of material’s fracture energy during impact test actually consists of the nucleation and crack growth energies, an attempt was made to use the impact strength instead of G in (1). After replacing G by KCU, relation (1) takes the form:

$$K_{1c} = B\sqrt{KCU \cdot E}\,, \tag{4}$$

where B - is the coefficient. At case of formation plane-deformed state of metal at the mouth of growing crack, Poisson's ratio (ν) or another quantity with its participation: $(1-\nu)$ [13,15] is used as B. After substituting in (4) instead of B $\nu = 0.25$ (for carbon steels average value of interval Poisson's ratio is 0.24-0.26), E = 202 GPa [8] and corresponding KCU values (Fig.2c), was calculated stress intensity factor. Result of ratio experimental values K_{1c} (Fig.2b) from calculated values according to (4) (denoted K_{1c}^{1}), shown in Fig. 3a,b. The presented relationships indicate a practically absent correlation between the calculated and experimental values of the critical stress intensity factor. A similar relationship between them was also obtained after substituting $B = (1-\nu)$ in (4). One of the reasons for lack of coincidence between K_{1c}^{1} and K_{1c} may be constancy of B, although their numerical values correspond approximately same order of magnitude. In general terms, the ν value, being the ratio of transverse to longitudinal deformations [8], characterises behaviour of material in region of uniform plastic flow. The metal at mouth of a growing crack (at determined K_{1c}) is in a plane-deformed state, and to a greater extent should be characterised by the ratio between elongation and narrowing in the region of local deformation. Given that by definition $\nu < 1$, the presence of metal in a triaxial stress state will lead to values greater than 1. Given that regulatory documents on railway wheels provide for use δ and ψ as quality parameters of metal, for fulfillment of condition of $B < 1$, is necessary to replace B in (4) on the ratio δ to ψ dependence:

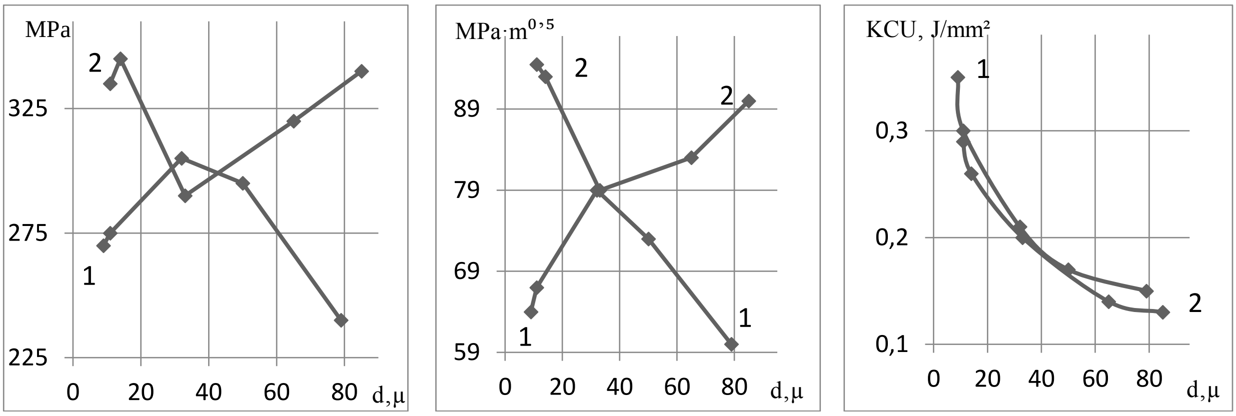
$$K_{1c}^{1} = \frac{1}{2}\left(\frac{\delta}{\psi}\right)\sqrt{KCU \cdot E} \tag{5}$$

Results of calculating K_{1c} value after substituting experimental values δ, ψ in (5) from Fig. 1c and KCU from Fig. 2c for the steels St. B and St. E, are presented in Fig. 3c, and for St. A, St. C and St. D in Fig. 4a. A comparative analysis of the obtained values indicates a better coincidence of values K_{1c}^{1} and K_{1c} in comparison with calculation according to dependence (4). To further verify fulfillment of dependence (5), experimental data current production of railway wheels were used (Fig. 4b). The calculation results according to (5) and experimental values K_{1c} for different carbon contents in steel showed a similar level of quality (Fig. 4c). In addition, existing differences in absolute values K_{1c} and K_{1c}^{1}, can be eliminated by account of the possible dependence of angular coefficient in relation (5) on additional characteristics. Thus, excluding complex operations for the manufacture of sample and its testing in the determination K_{1c}, it is possible to use the relation (5) to evaluate the critical stress intensity factor according to mechanical characteristics metal of the railway wheels current production.



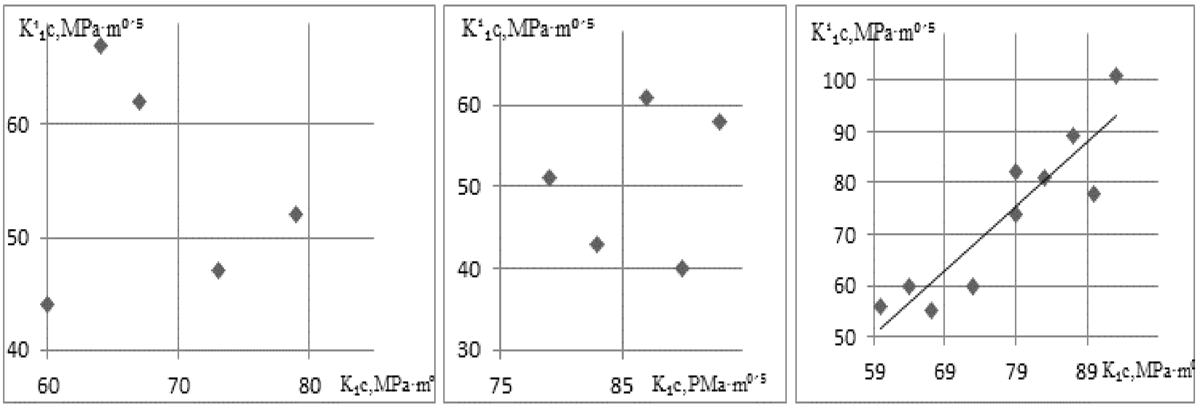
a b c

Fig. 1. Effect λ on ♦-σ_y, ■-σ_s (a); ■- K_{1c}, ♦-σ_{-1} (b); ♦-δ; ■-ψ (c),
where St. A-(1), St. C-(2), St. D-(3), (4)-St. B, (5)-St. E



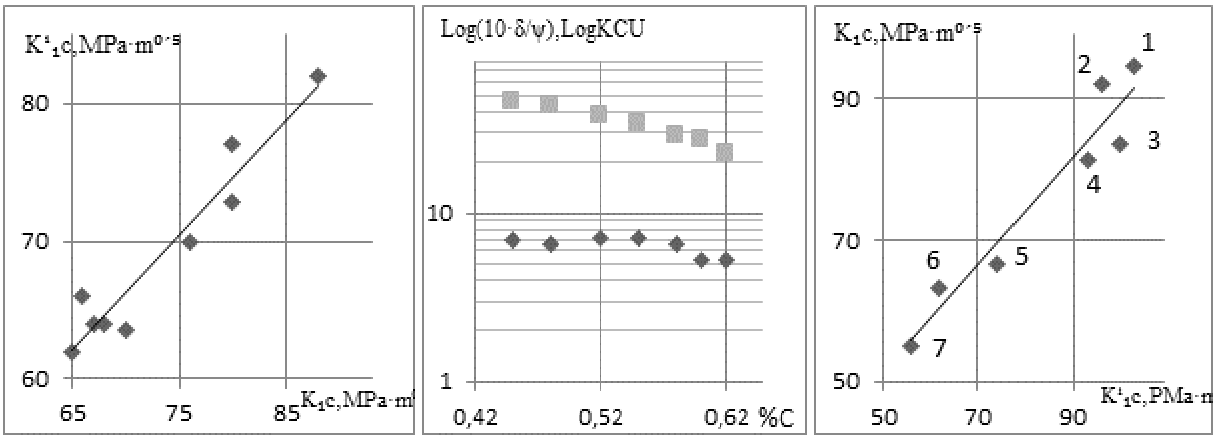
a **b** **c**

Fig. 2. The effect of austenite grain size on σ_{-1} (a), K_{1c} (b) and *KCU* (c),
where (1) - St. B, (2) - St. E



a b c

Fig. 3. Ratio between K_{1c} and K_{1c}^{1} calculated by the relation (4) at $B = \psi$ for
St. B (a), St. E (b); for $B=\frac{1}{2}(\frac{\delta}{\psi})$ by relation (5) of the same steels (St. B and St. E) (c)



a b c

Fig. 4. Relationship between K_{1c} and K_{1c}^{1} after calculation according to (5) for St. A, St. C, St. D (a), effect of carbon content in steel of the wheels of current production on δ/ψ -(♦), KCU (■)-(b) and corresponding values of K_{1c} and K_{1c}^{1} : 1-0.45 ; 2-0,48; 3-0,52; 4-0,55; 5-0,58; 6-0,6 and 7-0.62% C (c)

4. CONCLUSIONS

1. For carbon steel in isostructural state, effect of austenite grain size on impact strength exceeds dependence on carbon content.
2. To assess the critical stress intensity factor, a relationship is proposed based on the use of impact strength.
3. The proportionality coefficient in the proposed dependence is determined by ratio of elongation to narrowing at tensile test.

Gratitude

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