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Bending fatigue strength of steel with impurities range over 2 µm

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Abstract The parameters of high-grade steel are influenced by a combination of factors, including chemical composition and production technology. The impurity content is also a key determinant of the quality of high-grade steel. Non-metallic inclusions are one of the factors that influence the properties in particular fatigue strength of steel. The experimental material consisted of semi-finished products of medium-carbon structural steel. The production process involved three melting technologies: steel melting in a basic arc furnace with desulfurization or desulfurization and argon refining and in a oxygen converter and the next subjected to vacuum circulation degassing. This paper discusses the results of microstructural analyses, the changes in bending fatigue strength of steel hardened and tempered at different temperatures subjected to the size proportions and distances between the impurities of structural steel.

Key words – steel, structural steel, non-metallic inclusions, oxide impurities, fatigue strength, bending fatigue

1. Introduction

The combination of inner structural stresses caused by the presence of non-metallic inclusions and stresses resulting from external load plays an important role in the formation and development of fatigue cracks. Structural stresses are a function of inclusion structure. They are mostly affected by heat processing temperature when thermal stresses are formed along the inclusion-matrix (steel structure) boundary (CHICHKAREV E.A. 2009), (KLIMECKA-TATAR D., and all 2015), (ULEWICZ R. 2003) The intensity and rate of micro-crack formation and stress levels that cause fatigue cracking are determined by the resistance encountered by migrating dislocations. Tensile strength and material hardness are measures of that resistance (HANG J.M and all 2007), (HONGAND T. and all 2003), (PODORSKA D., WYPARTOWICZ J. 2008).

The composition of technical iron alloys is inclusive of sulfur and oxygen. Those elements form solutions in liquid metal. Then the presence of oxygen and non-metallic inclusions in steel is a natural consequences of physical and chemical processes during production. The shape of non-metallic inclusions may vary. Processes that cause the material to crack under periodically varying loads are stochastic events. As demonstrated by phenomenological research, the expansion of cracks resulting from fatigue is determined by the number of cycles, stress intensity and material properties (KIEDSSLING R. 1978), (LIPIŃSKI T. 2015a, 2015b), (MURAKAMI Y., ENDO M. 1994), (NODA N., MATSUO T. 2000), (SELEJDAK J., ULEWICZ R., INGALDI M. 2014).

Non-metallic inclusions play a special role in the process of steel hardening. In a correctly performed metallurgical process, non-metallic inclusions in steel are randomly distributed, and their quantity can be described by the distances between the impurities of steel, which was investigated in the present study.

2. Methods

The tested steel was manufactured in three industrial metallurgical processes. The resulting heats differed in purity and size of impurities as non-metallic inclusions. Heat treatments were selected to produce heats with different microstructure of steel. The steel was melted in a 140-ton basic arc furnace with desulfurized or desulfurized and refined with argon. In the second process, steel was melted in a 100-ton oxygen converter and deoxidized by vacuum. Billets with a square section of 100*x*100 mm were rolled with the use of conventional methods as a part of the second procedure.

Billet samples were collected to determine: chemical composition - the content of alloy constituents was estimated with the use of Leco quantometer and conventional analytical methods, and the relative volume of non-metallic inclusions with the use of the microscope under 400x magnification. It was determined for a larger boundary value of 2 μm.

Steel was austenitized for 30 minutes in the temperature of 880°C, and quenched in water afterwards. Tempering depended on warming the material for 120 minutes in the temperature of 200, 300, 400, 500 or 600°C, and cooling down on air. Fatigue strength was determined for all heats. The examination was conducted by calling out to rotatory curving machine with frequency of pendulum cycles: 6000 periods per minute. It was accepted that the basis was 10^7 cycles on fatigue defining endurance level. The level of fatigue-inducing load was adapted to the strength properties of steel. Maximum load was set for steel tempered at a temperature of: 200°C - 650 MPa, from 300°C to 500°C - 600 MPa, 600°C - 540 MPa (LIPIŃSKI T., WACH A., 2014, 2015a, 2015b). During the test, the applied load was gradually reduced in steps of 40 MPa (to support the determinations within the endurance limit). Load values were selected to produce 10^4-10^6 cycles characterizing endurance limits.

The arithmetic average size proportions and distances between the impurities of structural steel α were calculated with the use of the following formula (1):

$$\alpha = \frac{\bar{d}}{\lambda} \tag{1}$$

where: $\bar{d}$ – the average diameter of impurity, μm;
λ – arithmetic average impurities space.

Each of the heats λ was calculated with the use of the following formula (2):

$$\lambda = \frac{2}{3}\bar{d}\left(\frac{1}{V_0} - 1\right) \tag{2}$$

where: V_0 – the relative volume of impurities, %,
$\bar{d}$ – the average diameter of impurity, μm,
λ – arithmetic average impurities space.

The general form of the mathematical model is presented by equation (3):

$$Z_{go}=a\alpha+b \tag{3}$$

where: z_{go} – bending fatigue strength;
a, b – coefficients of the equation.

The significance of correlation coefficients r was determined on the basis of the critical value of the Student's t-distribution for a significance level α=0.05 and the number of degrees of freedom f = n-2.

3. Results and discussions

Statistically significant relationship bending fatigue strength of steel hardened and tempered at 200°C which depend on size proportions and distances between the impurities are presented in Fig. 1, regression equation and correlation coefficients r at (4).

$$z_{go(200)} = 0.79\,\alpha + 0.83 \tag{4}$$

Statistically significant relationship bending fatigue strength of steel hardened and tempered at 200°C which depend on size proportions and distances between the impurities are presented in Fig. 2, regression equation and correlation coefficients r at (5).

$$z_{go(300)} = 0.43\,\alpha + 0.83 \tag{5}$$

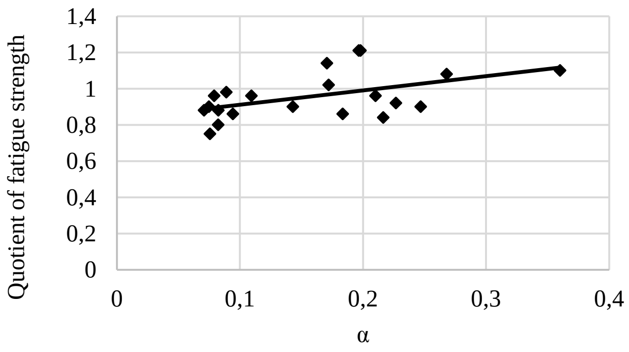

Fig. 1. Bending fatigue strength of steel hardened and tempered at 200°C subject to size proportions and distances between the impurities α

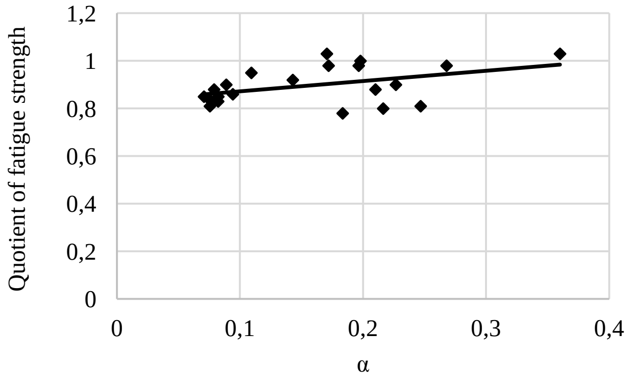

Fig. 2. Bending fatigue strength of steel hardened and tempered at 300°C subject to size proportions and distances between the impurities α

Statistically significant relationship bending fatigue strength of steel hardened and tempered at 200°C depending on size proportions and distances between the impurities are presented in Fig. 3, regression equation and correlation coefficients r at (6).

$$z_{go(400)} = 0.83\,\alpha + 0.80 \qquad (6)$$

Statistically significant relationship bending fatigue strength of steel hardened and tempered at 200°C which depend on size proportions and distances between the impurities are presented in Fig. 4, regression equation and correlation coefficients r at (7).

$$z_{go(500)} = 0.60\,\alpha + 0.80 \qquad (7)$$

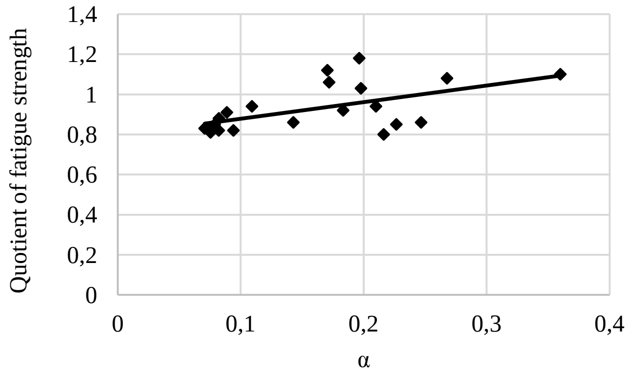

Fig. 3. Bending fatigue strength of steel hardened and tempered at 400°C subject to size proportions and distances between the impurities α

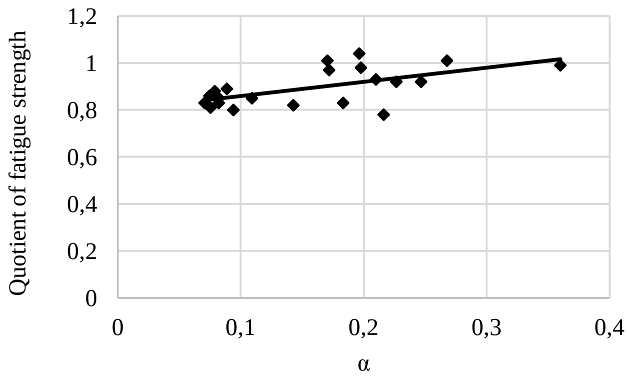

Fig. 4. Bending fatigue strength of steel hardened and tempered at 500°C subject to size proportions and distances between the impurities α

Statistically significant relationship bending fatigue strength of steel hardened and tempered at 200°C depending on size proportions and distances between the impurities are presented in Fig. 5, regression equation and correlation coefficients r at (8).

$$z_{go(600)} = 0.58\,\alpha + 0.84 \qquad (8)$$

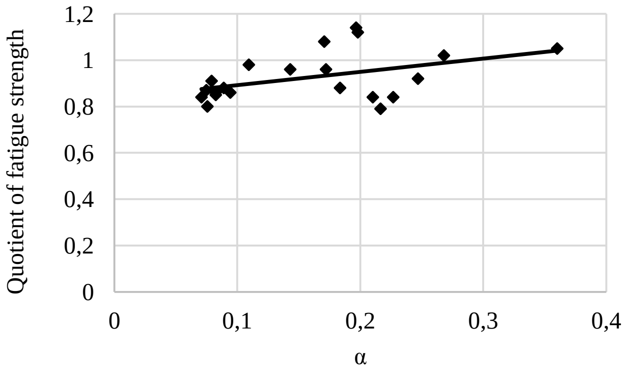

Fig. 5. Bending fatigue strength of steel hardened and tempered at 600°C subject to size proportions and distances between the impurities α

Statistically significant relationship bending fatigue strength of steel hardened and tempered at all temperatures depending on size proportions and distances between the impurities are presented in Fig. 6, regression equation and correlation coefficients r at (9).

$$z_{go(all)} = 0.65\,\alpha + 0.82 \qquad (9)$$

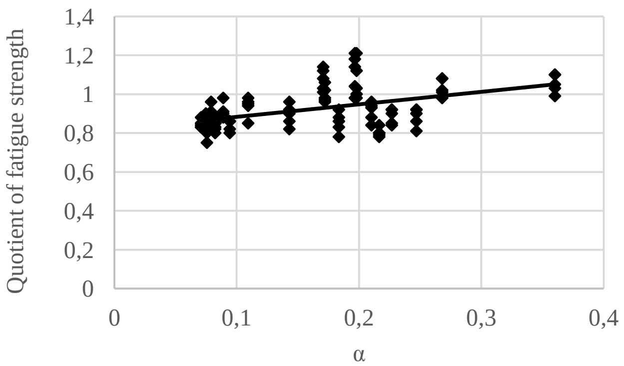

Fig. 6. Bending fatigue strength of steel hardened and tempered at all temperatures subject to size proportions and distances between the impurities α

4. Summary

The results of the study indicate that the presence of non-metallic inclusions larger than 2 μm, represented by the quotient of average diameter of impurity and arithmetic average impurities space α increases the magnitude of stress that induces fatigue cracking.

The use of the size proportions and distances between the impurities of structural steel α enhances the methodology for evaluating the influence degree of steel purity on fatigue strength of structural steel.

The results of the study indicate that fatigue strength, represented by fatigue strength during rotary bending, is correlated with the size proportions and distances between the impurities measuring larger than 2 μm. The presence of statistically significant correlations has been verified by Student's t-test.

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