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Influence of Impurity Morphology on the Fatigue Strength of High-Purity Structural Steel Melted in an Electric Furnace

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A modern user requires low operating costs, but also reliability from machines and technical devices. Reliability during the service life depends on the quality of construction solutions, but also largely on the quality, properties and adaptation to the working conditions used in the construction of construction materials. During the operation of technical objects, their a highly predictable wear occurs. The problem is the phenomena of premature wear and damage of elements. The causes of failure of technical facilities are usually complex and depend on many factors. They can include the human factor and the one related to the quality, selection, production and technological processes of the materials used in the construction of the facility. In real technical facilities, many premature failures are caused by material fatigue, which is related to the imperfection of the material and the morphology of non-metallic inclusions. The paper presents the change in fatigue strength for rotational bending of high-purity structural steel. In order to diversify the matrix of inclusions, the steel was hardened and tempered at temperatures from 200°C to 600°C. The influence of impurity diameter and arithmetic average impurities space on the fatigue strength of industrially produced steel was investigated..

Keywords: Steel, Fatigue Strength, Impurities, Arc Furnace

1 Introduction

The dynamic progress in manufacturing technology and available research methods recorded in recent years, along with the constantly growing demand for machines and technical devices characterized by high reliability, constitute the premise for conducting research on fatigue strength of construction materials [1-6]. Industrially produced steels contain in their chemical composition, in addition to alloying additives (which include Si, Mn, Cr, Mo, V, W, B and others), blends and impurities (such as S, P, O i inne) and other impurities introduced into the alloy as a result of Technological process (e.g. crumbs of furnace lining, chipping and ladle scale, etc.) as well as contaminants introduced during the re-remelting of metal alloys that were already in operation (e.g. hard ceramic particles embedded in metal alloys) [7-8]. The technological process aims to remove impurities by filtration, refining, etc. [9-11]. However, it is not easy. The economics of steel production, and therefore the desire to reduce its production costs, also limits these possibilities. Each cleaning operation of the metal alloy increases the production cost and, consequently, the price [12]. In the metallurgical process, physicochemical reactions take place, as a result of which non-metallic phases, called non-metallic inclusions, are formed in the liquid alloy. The number of non-metallic inclusions depends on the amount of impurities and impurities in the alloy. The qualitative structure of these inclusions as well as their shape and dimensions result not only from the content of impurities [13-16], but also from the production process [17-21].

Many factors affect the fatigue strength of metal alloys. In the literature, the most common information is the size and type of stress, load amplitude, interaction frequency, material microstructure, surface condition (e.g. roughness, corrosion), microstructural defects, working conditions and environment and the shape of the element [22-29].

Currently, the literature provides many hypotheses regarding the influence of individual factors on the fatigue strength. Safety coefficients were developed to compensate for random events and imperfections in knowledge and calculation methods. However, the influence of the material quality on the fatigue strength cannot be ignored. There is contamination in real material produced under industrial conditions. The content and morphology of these impurities is also an important factor determining the fatigue strength and thus durability of the material. Non-metallic inclusions usually reduce the fatigue properties of metal alloys [30-35]. However, there are reports of their beneficial effects [36-37].

Unfortunately, non-metallic contaminants mainly play a negative role. Despite the great interest of researchers in determining the relationship between inclusions and strength, in particular fatigue strength, it was not possible to clearly define this relationship. The presented knowledge is based on hypotheses [38-45]. It was confirmed that the fatigue strength of metal alloys depends not only on its microstructure, but also on the quantity and quality of non-metallic inclusions. The main role is played by the size and distribution of impurities in the microstructure of the material [33, 46, 47]. Despite the existence of advanced computer techniques [48,49] and many studies, until now it has not been possible to connect the fatigue strength with the morphology of inclusions occurring in high plasticity steel. Thanks to this, the topic presented in the paper is still relevant.

The aim of the research was to simultaneously investigate the influence of the average distance between inclusions and the relative volume of inclusions on the fatigue strength of high-purity structural steel with different microstructures.

2 Materials and methods

The test material was High-Purity Structural Steel Melted in an Electric Furnace with the addition of manganese, nickel, molybdenum and boron. It also contained phosphorus and sulfur impurity. The average content of individual alloying elements and impurities from 7 heats carried out in the electric arc furnace is shown in Table 1.

Tab. 1 *Real chemical composition of the tested steel*

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	B
0.26	1.18	0.24	0.02	0.01	0.52	0.50	0.25	0.15	0.03

It was decided to realize different hardness and plasticity of steel by applying different tempering temperatures. The steel intended for testing was smelted in a 140-ton electric arc furnace with desulfurization. The melts were carried out in industrial conditions. The molten steel was poured into the ladle. Then, billets with a section of 100 mm x 100 mm were rolled from it. Samples were taken from these billets for further research. The samples were quenched and tempered. In the hardening process, the steel was austenitized at the temperature of 880°C for 30 minutes. From this temperature, the samples were cooled in water. Then the samples were divided into batches and tempered at the following temperatures: 200, 300, 400, 500 and 600^{0}C for 120 minutes with air cooling. The fatigue strength test was carried out in the rotary bending process. The tests were carried out under load. The rotational speed of the bending machine was set at 600 revolutions per minute. The loading of the samples during bending was selected experimentally, taking into account the hardness of the steel. This load for appropriate tempering temperatures was: for 200^{0}C - 650 MPa, for 300 to 500^{0}C - 600 MPa and for 600^{0}C - 540 MPa [15,16,31,32].

The chemical composition was determined on each of the heats using a LECO quantometer and traditional chemical analysis methods. The relative volume of non-metallic inclusions with a minimum diameter of 2 μm was determined with a Quantimet video inspection microscope under 400x magnification. The relative total volume of non-metallic inclusions was determined by the chemical extraction method. The relative volume of inclusions in the range of up to 2 μm was calculated analytically by subtracting from the total volume of inclusions the volume obtained by image analysis with a diameter greater than 2 μm. The number of particles in the range 2 μm and smaller was the difference between the number of all inclusions determined by chemical extraction and the number of inclusions measured by the video method.

Calculations of the relative volume of non-metallic inclusions were carried out assuming that the quotient of particle surfaces and the observation area is equal to the quotient of the volume of particles in the assumed volume and the assumed volume.

The quality of non-metallic inclusions on the cross-section of the samples was determined using the XRD method. As a result of the research, it was found that Al_2O_3 was an average of 41.4% of impurities. Next, in terms of quantity, SiO_2 was found - 14.7% on average. The other types of inclusions in the form (in order of decreasing share) were: Cr_2O_3, CaO, FeO, MgO, MnO and constituted from 10% to 7% of the volume of all impurities. The qualitative structure of the particles present in the tested steel is presented in [13]. The distances between inclusions occurring in the tested α steel were calculated from the dependence (1). arithmetic average non-metallic inclusions space λ calculated in accordance to (2):

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

Where:

$\bar{d}$ …The average diameter of non-metallic inclusion [μm],

λ…rithmetic mean distance between non-metallic inclusion [μm].

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

Where:

V_0…The relative volume of impurities [%].

The correlation analysis and the significance assessment of the r coefficients were performed using the t-Student probability distribution for the significance level α = 0.05 and the number of degrees of freedom f = n-1. The critical value of the Student's distribution for p = (n-1) and the 5% significance level for 7 heats is tα (0.05) = 2.447.

The test results are presented in the form of a regression equation with the general form (3).

$$z_{go(tempered)} = a \cdot \alpha + b \quad (3)$$

Where:
a…Size and distances between the impurities [-],
a, b…Coefficients regresion equation [-].

3 Results and discussion

The total amount of impurities in the tested steels determined by the arithmetic mean of 7 heats was 0.188%, and its standard deviation was 0.0385%. Rotary bending fatigue strength high-purity structural steel melted in electric arc furnace after hardened with austenitized at temperature 880⁰C and tempered at 200°C as a relationship α taking into account the distance between the impurities present in the tested steel $\bar{d}$ and the arithmetic mean distance between non-metallic inclusion λ is presented at Fig. 1. Its regression equation and correlation coefficient r is presented at (4).

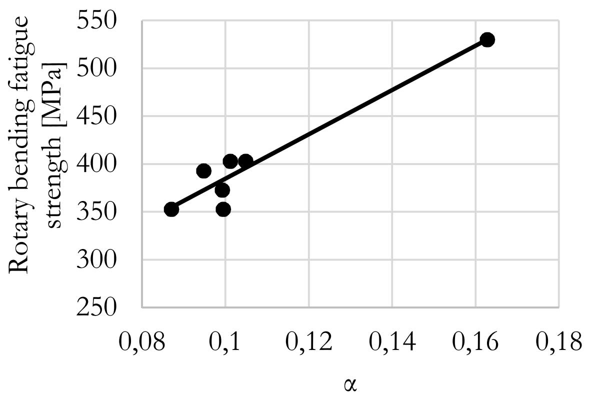

Fig. 1 *Rotational bending fatigue strength of hardened and tempered steel at 200°C as a function of diameter and distance between inclusions*

$$zgo_{(200)} = 2311.8 \cdot \alpha + 153.69, \; r=0.9566 \quad (4)$$

Rotary bending fatigue strength high-purity structural steel melted in electric arc furnace after hardened with austenitized at temperature 880⁰C and tempered at 200°C as a relationship α taking into account the distance between the impurities present in the tested steel d¯and the arithmetic mean distance between non-metallic inclusion λ is presented at Fig. 2. Its regression equation and correlation coefficient r is presented at (5).

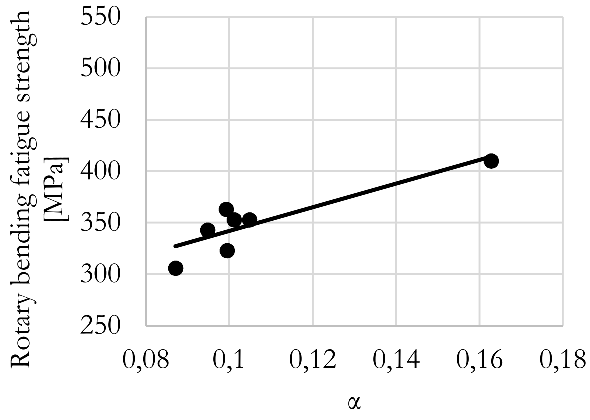

Fig. 2 *Rotational bending fatigue strength of hardened and tempered steel at 300°C as a function of diameter and distance between inclusions*

$$zgo_{(300)} = 1150.8 \cdot \alpha + 226.95, \; r=0.8812 \quad (5)$$

Rotary bending fatigue strength high-purity structural steel melted in electric arc furnace after hardened with austenitized at temperature 880⁰C and tempered at 200°C as relationship α taking into account the distance between the impurities present in the tested steel d¯and the arithmetic mean distance between non-metallic inclusion λ is presented at Fig. 3. Its regression equation and correlation coefficient r is presented at (6).

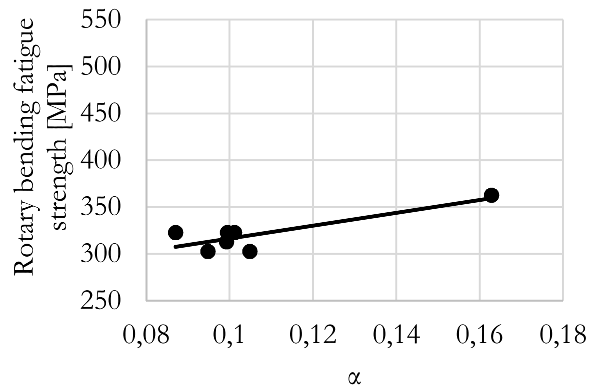

Fig. 3 *Rotational bending fatigue strength of hardened and tempered steel at 400°C as a function of diameter and distance between inclusions*

$$z_{go(400)} = 680.99 \cdot \alpha + 248.68, \; r=0.8433 \quad (6)$$

Rotary bending fatigue strength high-purity structural steel melted in electric arc furnace after hardened with austenitized at temperature 880⁰C and tempered at 200°C as relationship α taking into account the distance between the impurities present in the tested steel d¯and the arithmetic mean distance between non-metallic inclusion λ is presented at Fig. 4. Its regression equation and correlation coefficient r is presented at (7).

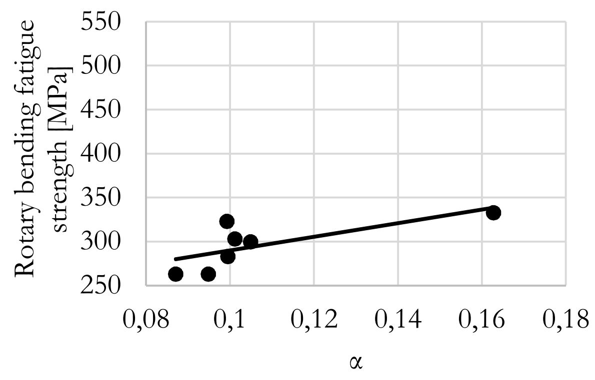

Fig. 4 *Rotational bending fatigue strength of hardened and tempered steel at 500°C as a function of diameter and distance between inclusions*

$$z_{go(500)} = 777.2 \cdot \alpha + 212.23, \ \ r=0.7146 \qquad (7)$$

Rotary bending fatigue strength high-purity structural steel melted in electric arc furnace after hardened with austenitized at temperature 880^{0}C and tempered at 200°C as relationship α taking into account the distance between the impurities present in the tested steel d¯and the arithmetic mean distance between non-metallic inclusion λ is presented at Fig. 5. Its regression equation and correlation coefficient r is presented at (8).

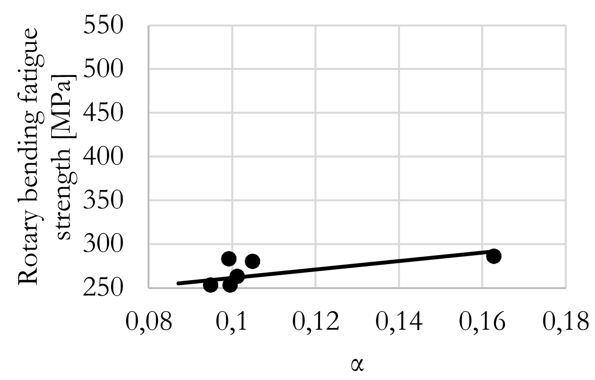

Fig. 5 *Rotational bending fatigue strength of hardened and tempered steel at 600°C as a function of diameter and distance between inclusions*

$$z_{go(600)} = 478.93 \cdot \alpha + 213.59, \ \ r=0.6417 \qquad (8)$$

The analysis of regression equations (4) - (8) and its correlation coefficients shows that the analyzed dependencies are well reflected by the first degree equation. By statistically analyzing the correlation coefficients, a strong a relationship is between bending fatigue strength and the alpha coefficient (two variables) was found. This relationship is stronger for the lower tempering temperatures. After the low tempering process at the temperature of 200^{0}C, the steel has the microstructure of low-tempered martensite [31]. As the tempering temperature increases, the microstructure of the steel, which is martensite, changes into medium-tempered martensite as a result of the transformation. Along with a further increase in the tempering temperature, high-tempered plastic martensite is formed. An increase in the tempering temperature causes an increase in plasticity and a decrease in hardness [31] due to the transformation of martensite.

Then the results of the research, a decrease in the level of correlation coefficients was observed along with an increase in the tempering temperature, therefore when the microstructure of the steel is closer to the diffusion one. Analyzing the regression equations for individual tempering temperatures, an increase in the α (3 - slope factor) coefficient was found with a decrease in the tempering temperature. With an increases the tempering temperature the steel, which is a matrix of non-metallic inclusions, gains plasticity. Thus, the relation matrix - non-metallic inclusion changes within a certain range [50]. By analyzing Fig. 1-Fig 5 with its regression equation (4) - (8) and its correlation coefficients, it was found that at lower tempering temperatures, and thus a harder matrix of pollutions, the accuracy of the analysis is higher. It follows that, apart from the lower complexity of the analysis of the results, the impact of pollutants on benging fatigue strength is greater. This is probably the reason for a thorough and quite simple analysis of the impact of impurities in the hard matrix on the benging fatigue strength of steel. This view confirms the great interest of researchers in steels of high hardness [18,29,34].

4 Conclusions

- The conducted tests in industrial conditions allow to bring the results and their analysis closer to the actual parameters prevailing in the industry.
- The α index relates the mean size of impurities with the mean distance between impurities and the relative volume of impurities, thus describing the influence of the morphology of pollution on the benging fatigue of steel.
- The strength of the influence of pollution depends on the hardness of the steel as a matrix of inclusions, and therefore the tempering temperature of the steel.

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