Research Article

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The effect of the impurities spaces on the quality of structural steel working at variable loads

<https://doi.org/10.1515/eng-2021-0024>

Received Jan 16, 2020; accepted Jul 04, 2020

Abstract: The quality of carbon steels working at variable loads mainly depend of microstructure, but also of impurities. The quantity and morphology of non-metallic inclusions and spaces between impurities are correlated with the content of admixtures in the alloy, while their phase composition and structure, in particular shape, dimensions and dispersion, are determined by the course of metallurgical processes. Non-metallic inclusions as impurities found in steel can affect its performance characteristics. Their impact depends not only on their quality, but also, among others, on their size and distribution in the steel volume. The literature mainly describes the results of tests on hard steels. The article discusses the results of a study investigating the effect of the number of large non-metallic inclusions (over 10 μm in size) on the fatigue strength of structural steel during rotary bending. The study was performed on 6 heats produced in an industrial plant. Fourteen heats were produced in 140 ton electric furnaces. All heats were desulfurized and refined with argon. The experimental variants were compared in view of the tempering the research steel. The fatigue strength of steel with an impurity spaces was determined during rotary bending: the results revealed that fatigue strength is determined by the impurity spaces and tempering temperature.

Keywords: steel, fatigue strength, impurities, non-metallic inclusions, quality of steel

1 Introduction

The research conducted so far shows that the material's resistance to fatigue depends on many factors, among which the most important are its strength properties, microstruc-

tural and structural structure as well as the amount and type of stress acting on the element or sample [1].

Analyzing the problem, it should be emphasized that the intensity of the formation of micro gaps and their growth rate, as well as the level of stress causing fatigue cracking of elements are determined by the resistance encountered by the dislocations moving in the material. The tensile strength or hardness of the material can be considered a measure of this resistance [2–4].

An important role in the creation and development of fatigue crack is played by the interaction of internal microstructural stresses, caused by the presence in steel of non-metallic inclusions, with stresses arising as a result of loading the element with external forces. Internal stresses are a function of the morphology of pollution. However, the conditions for heat treatment have a significant impact on their level, by creating thermal stress at the inclusion-matrix boundary (steel microstructure) [5–8].

A number of studies were devoted to tests of steel fatigue life with impurities occurring in its structure, the authors of which show negative impacts of inclusions [9–12]. It was also confirmed that the shape of non-metallic inclusions in steel has a significant impact on fatigue life [13, 14].

On the basis of SAE4340 steel tests carried out on the device causing rotational bending of the samples, it was found that the cracks began at the place of occurrence of aluminum-manganese inclusions, provided that they were in the vicinity of the sample surface. Inclusions greater than 6 μm were found in fatigue breakthrough foci. Hence, it was concluded that smaller inclusions do not adversely affect fatigue strength [12, 15].

A number of studies have found that [2, 16, 17]:

- the nucleation site of the cracks are 20 μm inclusions, located on or near the surface of the sample,
- there are three variants of nucleation of cracks with non-metallic inclusions:
 - conclusion cracks,
 - formation of discontinuities between phases boundaries in complex inclusions,
 - formation of micro-gaps between the inclusions and the matrix.

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- the development of a crack is usually the faster the lower the tempering temperature,
- the beginning of the crack was the inclusion phase – matrix.

One of the methods affecting the morphology of non-metallic inclusions in steel is the secondary metallurgy process [18, 19]. During it, there is a reduction of impurities present in steel. These impurities are the reason for reducing the durability of the material. In literature, the main emphasis is on low plasticity steels. Steels with high plasticity, for various reasons, are a rarer subject of research. Therefore, this paper focuses on steel with high plasticity and various microstructures obtained by different tempering variants. However, taking into account the fact that the durability of machine parts made of steel is determined not only by the total amount of impurities, but also their morphology, the steel was subjected to testing, in the manufacture of which secondary furnishings were applied. It was decided to include argon desulphurisation and refining in secondary metallurgy. The quality of steel under varying load is an important factor in both construction and technology those areas where high resistance on chemical wearing and mechanical fatigue of parts is desired e.g. in biotechnology equipment [22], anti-corrosion protection of fuel cells [23], power plants infrastructure [24] or implants [25]. It may also strongly impact on the management of industry processes [26–28] due to a change of parts lifetime, especially in a case of hydraulic actuators of heavy-duty machines [29–31]. Such modifications of material properties should be considered in the modeling of related control systems [32, 33], mechanical models [34] as well as in failure [35, 36], economy [37] and uncertainty [38, 39] analysis.

2 Methods

The steel was smelted in a 140 ton alkaline arc furnace. The metal drained into the ladle was desulfurized with a desulfex mixture. After casting the steel into a ladle, argon refining was used. Gas was blown through the porous body. The treatment time oscillated in the range of 8-10 minutes, after which the ingots were cast with a siphon method with a mass of 7 tons. After refining there were billets rolled from cast steel with a 100 × 100 mm square section.

Metallurgical semi-finished products from six melts were intended for research. 95 sections were taken from individual billets. Five were used to determine the chemical composition of steel and impurities present in it, while

the remaining ones were intended for metallographic and strength tests.

The total volume of non-metallic inclusions was determined by extraction method. Determination of the dimensional structure of impurities was carried out on an automatic stand for dimensional analysis using a Quantimet video microscope. A magnification of 400 times was used, evaluating sample fragments corresponding to 500 fields of view. A selective method of determining the relative volume of impurities was used. The resolving power of the microscope did not allow for effective consideration of pollutants having dimensions smaller than 2 μm in the assessment. Relative volumes of particles smaller than 2 μm were determined using the extraction method, which allows for the total determination of the content of all non-metallic particles in the tested steel. The amount of impurities determined using a video microscope and extraction for the range <10 μm was subtracted from the total amount of impurities determined by the chemical method. As a result, readings of non-metallic inclusions equal to or larger than 10 μm were obtained. The segregation occurring in technical iron alloys and the method used to determine the relative volume of impurities suggest that the features representing the inclusion structure should be treated as random variables. As a consequence, mathematical statistics methods were used in processing the data. When verifying statistical hypotheses, a level of significance was adopted limiting the probability of making an error to 5% ($\alpha = 0.05$) [9, 14, 40].

The general form of the mathematical model is presented by equation (1)

$$Z_{go(temp. tempered)} = a \cdot \lambda + b \quad (1)$$

where:

Z_{go} – rotating bending fatigue strength, MPa,

λ – impurities spacing, μm,

a, b – coefficients of the equation.

The dimensional structure of non-metallic inclusions was also presented using stereometric indicators known from the literature [15, 36]:

1. average contamination diameter:

$$\bar{d} = \frac{\pi}{2} \cdot \left(\frac{\sum n_i}{\sum (l_i)^{-1}} \right) \quad (2)$$

where:

n_i – the number of inclusions in the dimensional range,

l_i – average particle thickness, μm.

2. average free distance between secretions:

$$\bar{\lambda} = \frac{2}{3} \cdot \bar{d} \left(\frac{1}{V_v} - 1 \right) \quad (3)$$

where:

$\bar{d}$ – average contamination diameter, μm ,

V_v – relative volume of impurities, %.

Considering that the phase structure of the alloy and its physical properties exert an influence on the state of the material, decisive mainly not only about the sensitivity to non-metallic inclusions but also about its fatigue life, which for variable loads can be represented by fatigue resistance of low-alloy structural steel it was decided to subject the material to heat treatment.

Samples from individual melts were divided into five parts. A different treatment method was used for each of them. It consisted of:

- quenching in which austenitizing was carried out for 30 min. at 880°C , after which the samples were cooled in water;
- tempering hardened steel for 120 minutes at 200, 300, 400, 500 and 600°C with air cooling.

The use of tempering in a wide temperature range was intended to take into account various microstructures and corresponding strength levels of the material. Heat treatment was carried out in an electric chamber furnace. Tests of strength properties were carried out by simulating events that cause material fatigue in the exploited machine elements.

Smooth samples with constant cross section and diameter of 10 mm were used. They were made according to the principles given in PN-76 / H-04326. The tests were carried out on the MUJ 6000 machine, which, as a result of rotary bending, caused variable stresses with a pendulum cycle at a frequency of 6000 cycles per minute. The value of 10^7 cycles was adopted as the basis for determining the conventional limit of fatigue strength. By gradually changing stress levels causing fatigue (σ), the numbers of oscillations (N) causing destruction of the sample and the arbitrary fatigue limits σ_g enabling durability higher than 10^7 cycles were determined.

The features representing fatigue properties were:

- durability, $\lg N$,
- ultimate stress for the level of 10^7 cycles,

When comparing statistical parameters and relationships between features, t-Student or F-Fischer-Snedecor distributions were used.

Stress values causing fatigue were adapted to the strength properties of steel. Their upper limits were [14, 40]:

- In the case of steel tempered at 200°C – 650 MPa
- For tempered steels at 300°C – 500°C – 600 MPa
- After tempering at 600°C – 540 MPa

During the tests, stress was gradually reduced, maintaining a gap of 40 MPa between levels (they allowed to obtain results in the field of limited fatigue strength).

The values were chosen in such a way that the number of cycles characterizing limited fatigue strength oscillated around 10^4 – 10^6 .

3 Result

The steel was smelted in a 140 ton alkaline arc furnace with a desulfex mixture and after casting the steel into a ladle, argon refining was used has impurities. The effect of impurities is closely related to the processes taking place in micro-areas, which is why the size of inclusion particles significantly influences the properties of constructional materials. The average chemical composition of the analysed steel is presented in Table 1.

Bending fatigue strength of steel hardened and tempered at 200°C in depends of impurities space are presented in Figure 1, regression equation and correlation co-

Figure 1: Bending fatigue strength of steel hardened and tempered at 200°C subject to impurities space

Table 1: Average chemical composition of the analysed steel

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	B
wt %									
0.23	1.20	0.27	0.021	0.011	0.46	0.46	0.22	0.14	0.003

Figure 2: Bending fatigue strength of steel hardened and tempered at 300°C subject to impurities space

Figure 3: Bending fatigue strength of steel hardened and tempered at 400°C subject to impurities space

Figure 4: Bending fatigue strength of steel hardened and tempered at 500°C subject to impurities space

Figure 5: Bending fatigue strength of steel hardened and tempered at 600°C subject to impurities space

Figure 6: Bending fatigue strength of steel hardened and tempered at 200, 300, 400, 500 and 600°C subject to impurities space

efficients r at (4).

$$z_{go(200)} = -0.6471 \cdot \lambda + 543.22, \quad r = 0.7776 \quad (4)$$

Bending fatigue strength of steel hardened and tempered at 300°C in depends of impurities space are presented in Figure 2, regression equation and correlation coefficients r at (5).

$$z_{go(300)} = -0.3381 \cdot \lambda + 418.34, \quad r = 0.7577 \quad (5)$$

Bending fatigue strength of steel hardened and tempered at 400°C in depends of impurities space are presented in Figure 3, regression equation and correlation coefficients r at (6).

$$z_{go(400)} = -0.4698 \cdot \lambda + 430.37, \quad r = 0.9014 \quad (6)$$

Bending fatigue strength of steel hardened and tempered at 500°C in depends of impurities space are presented in Figure 4, regression equation and correlation coefficients r at (7).

$$z_{go(500)} = -0.3666 \cdot \lambda + 355.04, \quad r = 0.9308 \quad (7)$$

Bending fatigue strength of steel hardened and tempered at 600°C in depends of impurities space are presented in Figure 5, regression equation and correlation coefficients r at (8).

$$z_{go(600)} = -0.3481 \cdot \lambda + 323.66, \quad r = 0.8818 \quad (8)$$

Bending fatigue strength of steel hardened and tempered at 200, 300, 400, 500 and 600°C in depends of impurities space are presented in Figure 6, regression equation and correlation coefficients r at (9).

$$z_{go(200,300,400,500,600)} = -0.434 \cdot \lambda + 414.13, \quad r = 0.4070 \quad (9)$$

Parameters representing mathematical models and correlation coefficients are presented in Table 2.

Table 2: Parameters representing mathematical models and correlation coefficients

Tempering temperature °C	Regression coefficient a (1)	Regression coefficient b (1)	Correlation coefficient r	$t_{\alpha=0.05}$	$t_{\alpha=0.05}$ from Student's distribution for $p=(n-1)$
200	0.6471	543.22	0.7776	2.7654	2.571
300	0.3381	418.34	0.7577	2.5962	
400	0.4698	430.37	0.9014	4.6551	
500	0.3666	355.04	0.9308	5.6940	
600	0.3481	323.66	0.8818	4.1808	
all	0.434	414.13	0.407	2.3995	2.045

Analysis of the a and b coefficients (Table 2) in the regression equations (1) indicates that the fatigue strength (parameter b) and the impact of impurities spacing represented by the parameter and decrease with increasing tempering temperature, and thus plasticizing the steel microstructure.

Analyzing the changes in bending fatigue strength (Figure 1 – Figure 6) it was found that its size decreased as the tempering temperature increased. It has also been noted that as impurities spacing increases, bending fatigue strength decreases. This is correct because with a constant share of non-metallic inclusions in the steel microstructure, together with the increase in impurities spacing, the size of non-metallic inclusions must increase, the increase of which is the reason for the reduction of the fatigue strength of the material.

Bending fatigue strength of steel hardened and tempered at 200, 300, 400, 500 and 600°C subject to impurities space is also statistically significant and can be used for analysis when steel heat treatment parameters or its microstructure are not known. However, taking into account the considerable dispersion of the location of measuring points, it is recommended to use graphs corresponding to the properties of steel.

Statistical analysis was performed for unfavorable (statistically) mean values from melts. For more trials, the critical values of the Student's t test are lower, and therefore the relationships are more statistically significant.

4 Conclusion

On the basis of the obtained test results it was found: there is a correlation between fatigue strength represented by fatigue strength with swinging bending and impurities spacing with dimensions larger than 10 μm . The validity of the application was verified by assessing the significance of correlation coefficients by the Student's t method. Fa-

tigue strength is statistically significantly associated with impurities spacing. The higher the tempering temperature, therefore lower the hardness of the steel, the smaller the dispersion of results around the regression line. Rotational bending fatigue strength increases with a decrease in impurities spacing, thereby increasing the dimensions of non-metallic inclusions. The highest flexural fatigue strength was recorded for the lowest tempering temperature, *i.e.* 200°C.

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