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# INFLUENCE OF LARGE NON-METALLIC INCLUSIONS ON BENDING FATIGUE STRENGTH HARDENED AND TEMPERED STEELS

## ABSTRACT

The article discusses the effect of large oxide impurities (a diameter larger than 10 μm in size) on the fatigue resistance of structural steel of high purity during rotary bending. The study was performed on 7 heats produced in an industrial plant. The heats were produced in 140 ton electric furnaces. All heats were desulfurized.

The experimental material consisted of semi-finished products of high-grade, carbon structural steel with: manganese, chromium, nickel, molybdenum and boron. Steel sections with a diameter of 18 mm were hardened from austenitizing by 30 minutes in temperature 880°C and tempered at a temperature of 200, 300, 400, 500 and 600°C for 120 minutes and air-cooled. The experimental variants were compared in view of the heat treatment options. Fatigue tests were performed with the use of a rotary bending machine at a frequency of 6000 cpm. The results were statistical processed and presented in graphic form.

This paper discusses the results of the relative volume of large impurities, the fatigue strength for various heat processing options.

**Keywords:** carbon steel, inclusions, non-metalic inclusions, fatigue strength, bending fatigue strength

## INTRODUCTION

To ensure an appropriately high reliability of machine parts, research has been conducted on the effect of impurities on the performance characteristics of a construction material and its durability. The presence of oxygen and non-metallic inclusions in steel is a natural consequences of physical and chemical processes during production. Commercial iron alloys apart of typical chemical elements contain sulfur, oxygen, and those elements form solutions in liquid metal. The physical and chemical reactions that occur in the process of steel melting and solidification produce non-metallic compounds and phases, referred to as inclusions [1-4].

Industrially melted steel contains non-metallic inclusions. The quality, quantity and size of inclusions can be controlled, but such impurities cannot be eliminated in their entirety because they are natural components of the phases present in alloys. Although steel has a relatively small number of non-metallic inclusions, those impurities have a considerable impact on the material's technological and strength parameters, in particular fatigue strength and life. During processing, the shape and distribution of microparticles change, and impurities undergo anisotropic deformation. Non-metallic inclusions play a special role in the process of steel hardening. Due to differences in the physical properties of steel and inclusion-forming phases, structural stresses are formed along inclusion boundaries. Fatigue cracking is caused by local discontinuities which are transformed into micro-cracks and cause material decohesion [2,5].Fatigue occurs and develops gradually due to cyclic service load that causes stress. Initial stages are marked by the incubation of slips whose number increases in individual grains. When critical values are exceeded, the material cracks and becomes fit for scrap [1,6-9].

Steel of various purity grades is manufactured for the production of elements that operate under different conditions. Expensive high-grade steel is not used in common applications. Steel used in structures which are exposed to low loads may contain significant amounts of impurities that do not compromise the functional parameters of steel. Some applications require high-grade and high-purity steel that guarantees structural reliability and safety. The allowable impurity content of steel, the morphology of impurities and their influence on steel strength (mainly under variable loads) have been analyzed by numerous authors. Despite years of research and analyses, our knowledge of the impact of non-metallic inclusions on the properties of steel elements is still ambiguous and limited [5,10-12].

The aim of this study was to determine the influences of large non-metallic inclusions on bending fatigue strength hardened and tempered performed on industrially manufactured high-grade, carbon structural steel of high purity.

## MATERIALS AND EXPERIMENTAL PROCEDURE

Analyses of fatigue stress with an oscillating cycle were carried out in accordance with Polish Standard PN-76/H-04326 using smooth steel samples with a fixed cross-section diameter of 10 mm. The applied analytical methodology was described by [13].

The tested material comprised steel manufactured in arc furnace with out-side treatment. Heat treatments were selected to produce heats with different microstructure of steel, from hard microstructure of tempered martensite, through sorbitol to the ductile microstructure of spheroidite.

Steel was melted in a 140-ton basic arc furnace. The study was performed on 7 heats produced in an industrial plant. Pig iron was ca. 25% of the charge and the rest came from scrap. The metal was tapped into a ladle, it was desulfurized with a Desulfex mixture and 7-ton ingots were uphill teemed. Billets with a square section of 100x100 mm were rolled with the use of conventional methods. Billet samples were collected to determine:

- chemical composition. The content of alloy constituents was estimated with the use of LECO analyzers, an AFL FICA 31000 quantometer and conventional analytical methods;
- dimensions of impurities by inspecting metallographic specimens with the use of a Quantimet 720 video inspection microscope under 400x magnification. It was determined for a larger boundary value of 10 μm.

Analytical calculations were performed on the assumption that the quotient of the number of particles on the surface divided by the area of that surface was equal to the quotient of the number of particles in volume divided by that volume [14].

A total of 51 sections were examined to determine the fatigue strength of all heats. The analyzed sections had a cylindrical shape and a diameter of approximately 10 mm. Their main axes were oriented in the direction of processing. The sections were thermally processed to determine differences in their structural characteristics. They were hardened for 30 minutes from the austenitizing temperature of 880°C and quenched in water. The analyzed samples were tempered for 120 minutes at a temperature of 200, 300, 400, 500 or 600°C and cooled in air.

Fatigue strength was determined for all heats. Heat treatment was applied to evaluate the effect of hardening on the fatigue properties of the analyzed material, subject to the volume of fine non-metallic inclusions. The application of various heat treatment parameters led to the formation of different microstructures responsible for steel hardness values in the following range from 271 to 457 HV [7].

Examination was realized on a rotary bending fatigue testing machine at 6000 rpm. The endurance (fatigue) limit was set at $10^7$ cycles. The level of fatigue-inducing load was adapted to the strength properties of steel. Maximum load was set at:

- for steel tempered at a temperature of 200°C – 650 MPa,
- for steel tempered at a temperature of 300°C – 500°C – 600 MPa,
- for steel tempered at a temperature of 600°C – 540 MPa.

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 [2].

The dimensions of non-metallic inclusions were described by stereometric parameters. The analysis focused on oxygen due to the predominance of oxygen inclusions. The percentage of sulfur-based inclusions was below the value of error in determinations of the percentage of oxygen-based inclusions, therefore, sulfur-based inclusions were excluded from further analyses. The main focus of the analysis was on oxygen-based inclusions.

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

$$z_{go\,(\text{temp. tempered})} = a\,V + b \tag{1}$$

where: $z_{go}$ – rotating bending fatigue strength, MPa,
$V$ – relative volume of inclusions define by metallography method for a diameter larger than 10 μm in size, %,
a, b – coefficients of the equation.

The significance of correlation coefficients r was determined based of the critical value of the Student's t-distribution for a significance level of $\alpha$=0.05 and the number of degrees of freedom f = n-2 by formula (2).

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \tag{2}$$

The values of the diffusion coefficient $z_{go}$ near the regression line were calculated with the use of the below formula (3):

$$\delta = 2s_{zgo}\sqrt{1-r^2} \tag{3}$$

where: $s_{zgo}$ – standard deviation ,
r – correlation coefficient.

## RESULTS

The average chemical composition of heats is presented in Table 1. The impurity content of steel was low phosphorus levels did not exceed 0.025% and sulphur levels did not exceed 0.02%. Research steel had 0.192% vol. non-metallic inclusions [5,15]. Relative volume of non-metallic inclusions measuring over 35 µm were in limit of error.

Bending fatigue strength of steel hardened and tempered at all ranges temperatures (200, 300, 400, 500 and 600°C) in depends of volume of inclusions larger than 10 µm are presented in Fig. 1, regression equation and correlation coefficients r at (4).

***Table 1.*** *Average chemical composition of research steel*

| Chemical composition [wt. %] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| C | Mn | Si | P | S | Cr | Ni | Mo | Cu | B |
| 0.26 | 1.18 | 0.24 | 0.020 | 0.011 | 0.52 | 0.50 | 0.25 | 0.15 | 0.0027 |

$$z_{go} = 2049.6\ V_{w>10} + 201.76 \text{ and } r = 0.4196 \tag{4}$$

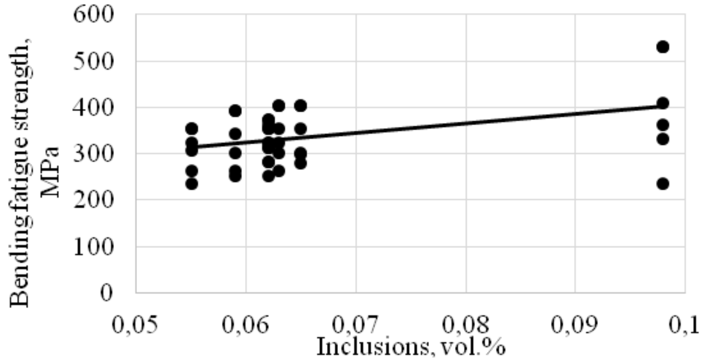

**Fig. 1.** Bending fatigue strength of steel hardened and tempered at 200, 300, 400, 500 and 600°C subject to volume of inclusions larger than 10 µm

Bending fatigue strength of steel hardened and tempered at 200°C in depends of volume of inclusions larger than 10 µm are presented in Fig. 2, regression equation and correlation coefficients r at (5).

$$z_{go\ (200)} = 4053.4\ V_{w>10} + 132.46 \text{ and } r = 0.9583 \tag{5}$$

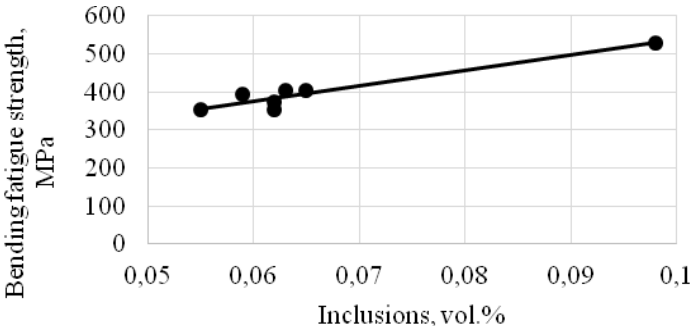

**Fig. 2.** Bending fatigue strength of steel hardened and tempered at 200°C subject to volume of inclusions larger than 10 µm

Bending fatigue strength of steel hardened and tempered at 300°C in depends of volume of inclusions larger than 10 µm are presented in Fig. 3, regression equation and correlation coefficients r at (6).

$$z_{go\ (300)} = 2020.9\ V_{w>10} + 216.18 \text{ and } r = 0.8810 \quad (6)$$

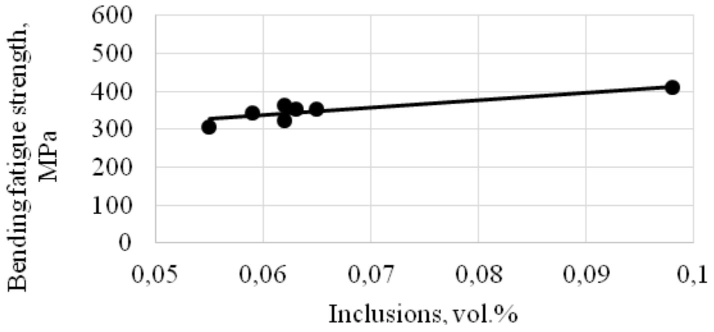

**Fig. 3.** Bending fatigue strength of steel hardened and tempered at 300°C subject to volume of inclusions larger than 10 µm

Bending fatigue strength of steel hardened and tempered at 400°C in depends of volume of inclusions larger than 10 µm are presented in Fig. 4, regression equation and correlation coefficients r at (7).

$$z_{go\ (400)} = 1200.3\ V_{w>10} + 242.01 \text{ and } r = 0.8462 \quad (7)$$

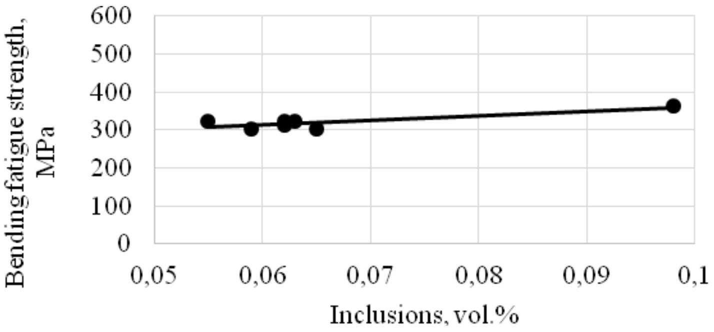

**Fig. 4.** Bending fatigue strength of steel hardened and tempered at 400°C subject to volume of inclusions larger than 10 µm

Bending fatigue strength of steel hardened and tempered at 500°C in depends of volume of inclusions larger than 10 µm are presented in Fig. 5, regression equation and correlation coefficients r at (8).

$$z_{go\ (500)} = 1409.2\ V_{w>10} + 200.59 \text{ and } r = 0.7791 \qquad (8)$$

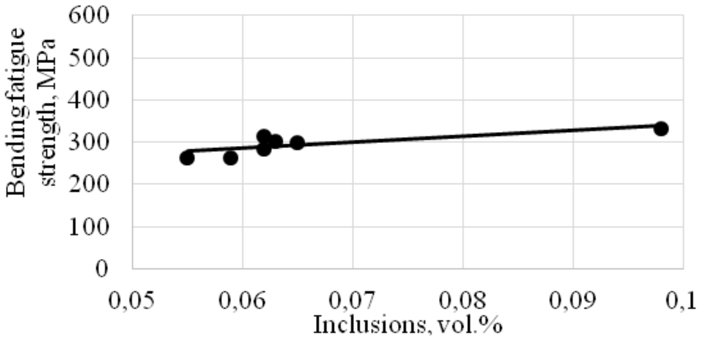

**Fig. 5.** Bending fatigue strength of steel hardened and tempered at 500°C subject to volume of inclusions larger than 10 µm

Bending fatigue strength of steel hardened and tempered at 600°C in depends of volume of inclusions larger than 10 µm are presented in Fig. 6, regression equation and correlation coefficients r at (9), but it is statistically insignificant for level α=0.05.

$$z_{go\ (600)} = -\ 439.87\ V_{w>10} + 286.87 \text{ and } r = 0.3333 \qquad (9)$$

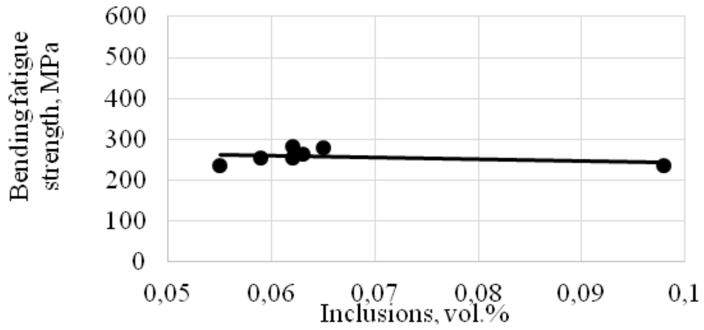

**Fig. 6.** Bending fatigue strength of steel hardened and tempered at 600°C subject to volume of inclusions larger than 10 µm

## CONCLUSIONS

An analysis of coefficients *a* and *b* (1) in regression equations (4-9) indicates that fatigue strength (parameter *b*) decreases and that the effect of large non-metallic inclusions (parameter *a*) increases with a rise in tempering temperature.

The results of this study indicate that fatigue strength, represented by fatigue strength under rotary bending conditions, is correlated with the relative volume of non-metallic inclusions larger than 10 µm and a tempering temperature of 200-500$^{o}$C. The presence of statistically significant correlations was verified by Student's t-test.

The present findings support the conclusion that non-metallic inclusions larger than 10 µm (up to 30 µm in this study) with a very low relative volume inhibit the propagation of fatigue cracks.

An increase in tempering temperature lowers steel hardness, increases steel plasticity and increases dispersion values along the regression line for inclusions larger than 10 µm.

The presence of non-metallic inclusions larger than 10 µm does not increase the magnitude of stress that induces fatigue cracking, but the final outcome is also determined by the strength and plasticity of the metallic groundmass.

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