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T. LIPIŃSKI*#

THE EFFECT OF THE DIAMETER AND SPACING BETWEEN IMPURITIES ON THE FATIGUE STRENGTH COEFFICIENT OF STRUCTURAL STEEL

The article discusses the effect of the diameter and spacing between impurities (size up to 2 μm) on the fatigue strength coefficient of structural steel during rotary bending. The study was performed on 21 heats produced in an industrial plant. Fourteen heats were produced in 140 ton electric furnaces, and 7 heats were performed in a 100 ton oxygen converter. All heats were desulfurized. Seven heats from electrical furnaces were refined with argon, and heats from the converter were subjected to vacuum circulation degassing. Steel sections with a diameter of 18 mm were hardened for 30 minutes from the austenitizing temperature of 880°C and tempered at a temperature of 200, 300, 400, 500 and 600°C. The experimental variants were compared in view of the applied melting technology and heat treatment options. The results were presented graphically and mathematically to account for the correlations between the fatigue strength coefficient during rotary bending, the diameter of and spacing between submicroscopic impurities. Equations for calculating the fatigue strength coefficient at each tempering temperature and a general equation for all tempering temperatures were proposed. Equations for estimating the fatigue strength coefficient based on the relative volume of submicroscopic non-metallic inclusions were also presented. The relationship between the fatigue strength and hardness of high-grade steel vs. the quotient of the diameter of impurities and the spacing between impurities, and the fatigue strength and hardness of steel vs. the relative volume of submicroscopic non-metallic impurities were determined.

Keywords: steel, structural steel, non-metallic inclusions, oxide impurities, fatigue strength coefficient, bending fatigue

1. Introduction

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. Inclusions may also play an important role, subject to their type and shape. Inclusions may increase the strength of steel by inhibiting the development of micro-cracks. Yet as regards steel, non-metallic inclusions have mostly a negative effect which is dependent on their content, size, shape and distribution [1-3]. The mechanical properties and fatigue strength of structural materials should also be evaluated in view of crystallization conditions [4-9], manufacturing process [10-12], microstructure [13,14], microsegregation [15-19] and the existing defects [20-22].

The distribution of inclusions is an equally important factor. Single inclusions and clusters of inclusions exert different effects. Large, individual inclusions can produce discontinuities that grow rapidly under variable load. The clusters of microparticles of a subcritical size lower stress and increase the number of sample-damaging cycles [23-28].

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. The presence of oxygen and non-metallic inclusions in steel is a natural consequences of physical and chemical process during production. The shape of non-metallic inclusions may vary. Spheroidal inclusions (type I) are characteristic of steel which contains high levels of oxygen. The addition of small amounts of aluminum leads to partial deoxidation of steel and the formation of inclusions (type II) along the boundaries of austenite grains. Excessive amounts of powerful deoxidants contribute to the formation of large faceted inclusions (type III) [5,29-31].

The quantity of non-metallic inclusions in steel is relatively low, nevertheless, they have a significant impact on the structure, technological and strength parameters of the resulting alloy. The effect of impurities is closely related to the processes taking place in micro-areas, which is why the size of inclusion significantly influences the properties of construction materials [32-35].

Alloys subjected to variable loads require high-grade steels. Their properties are determined during complex tests that are expensive and time consuming. For this reason, analyses that support quick determination of the evaluated properties are often used in industrial units. Fatigue strength is one of the evaluated properties of steel. Various functions, nomograms and coefficients are given in the literature for estimating fatigue strength as a function of tensile strength [36].

* UNIVERSITY OF WARMIA AND MAZURY IN OLSZTYN, FACULTY OF TECHNICAL SCIENCES, 11 OCZAPOWSKIEGO STR., 10-957 OLSZTYN, POLAND

Corresponding author: tomaszlipinski.tl@gmail.com

Various functions are also used to convert fatigue strength for a known load cycle, usually rotary bending, into fatigue strength for a different load cycle, such as one-sided bending based on the results of rotary bending.

Those relationships are presented for different group of materials, production processes, heat processing methods, etc. They include other sensitivity coefficients such as the coefficient of material's sensitivity to cycle asymmetry, load type, etc. The presented analytical relations are expressed by the influence coefficient c which is written as follows in equation (1) when ultimate tensile strength R_m considered:

$$z_g = cR_m \tag{1}$$

To estimate tensile strength based on the results of non-destructive tests, coefficient p was introduced in equation (2) to determine tensile strength as a function of hardness.

$$R_m = pHV \tag{2}$$

Equation (1) does not account for steel purity. For this reason, coefficient c may equals on a broad range of values. For steel samples subjected to rotary bending, it ranges from 0.36 to 0.6 of tensile strength R_m [1].

Coefficients c and p were substituted with coefficient k to convert equation (2) to (1). Coefficient k is the quotient of fatigue strength z_g divided by Vickers hardness HV (3).

$$k = \frac{z_g}{HV} \tag{3}$$

The influence of impurities on fatigue strength has been researched extensively, but very few studies investigate the effect of impurities on the coefficient given by equation (3) which is used to estimate fatigue strength based on hardness, i.e. in non-destructive tests.

In this study, attempts were made to analyze the impact of impurities with various diameters and spacing λ on fatigue strength coefficient k determined under rotary bending fatigue conditions z_{go}.

2. Methods

The study was carried out in an industrial setting with the aim of reproducing analytical results on an industrial scale. The analyzed material was structural carbon steel. The tested material comprised steel manufactured in three different metallurgical processes. The resulting heats differed in purity and size of non-metallic inclusions. Heat treatments were selected to produce heats with different microstructure, from microstructure of tempered martensite, through sorbite to the ductile microstructure obtained by spheroidization. Pig iron accounted for approximately 25% of the charge. The study was performed on 21 heats produced in an industrial plant.

In the first process, steel was melted in a 140-ton basic arc furnace. The metal was tapped into a ladle, it was desulfurized and 7-ton ingots were uphill teemed. Billets with a square section of 100×100 mm were rolled with the use of conventional methods. As part of the second procedure, steel was additionally refined with argon after tapping into a ladle. Gas was introduced through a porous material, and the procedure lasted for 8-10 minutes. Steel was poured into moulds, and billets were rolled similarly as in the first stage. In the third process, steel was melted in a 100-ton oxygen converter and deoxidized with vacuum. Steel was cast continuously and square 100×100 mm billets 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, relative volume of non-metallic inclusions with the use of the extraction method, dimensions of impurities by inspecting metallographic specimens with the use of a Quantimet 720 video inspection microscope under 400× magnification. It was determined for a larger boundary value of 2 μm. The number of particles measuring 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. 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 [38].

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.

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 from the 30 minutes austenitizing temperature of 880°C and quenched in water. The samples were tempered for 120 minutes at a temperature of 200, 300, 400, 500 or 600°C.

Fatigue strength was determined for all heats. Heat treatment was realized 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 [30].

The test was performed 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 for steel tempered at a temperature of 200°C – 650 MPa, from 300°C to 500°C – 600 MPa and for 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 [1].

The arithmetic average size proportions and distances between the impurities of structural steel α were calculated with the use of the below formula (4):

$$\omega = \frac{\overline{d}}{\overline{\lambda}} \tag{4}$$

where:

$\overline{d}$ – average diameter of impurity, μm;

$\overline{\lambda}$ – arithmetic average distance between impurities, μm.

The arithmetic average distances between impurities for each of the heats $\overline{\lambda}$ were calculated with the use of the below formula (5):

$$\overline{\lambda} = \frac{2}{3}\overline{d}\left(\frac{1}{V_0} - 1\right) \tag{5}$$

where:

$\overline{d}$ – average diameter of impurity, μm,

V_0 – relative volume of submicroscopic impurities, %.

The general form of the mathematical model is presented by equations (6) and (7)

$$k_{\text{(tempering temperature)}} = a\,\alpha + b \tag{6}$$

and

$$V_0 = g\,\alpha + h \tag{7}$$

where:

k – fatigue strength coefficient,

ω – arithmetic average size proportions and distances between impurities in structural steel,

V_0 – relative volume of non-metallic inclusions measuring 2 μm and smaller, vol. %

a, b, g, h – coefficients of the equation.

The significance of correlation coefficients r was determined based on the critical value of the Student's t-distribution for a significance level of $\alpha = 0.05$ and the number of degrees of freedom $f = n - 2$ using formula (8).

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \tag{8}$$

The values of diffusion coefficient z_{go} near the regression line were calculated with the use of the below formula (9):

$$\delta = 2s\sqrt{1-r^2} \tag{9}$$

where:

s – standard deviation,

r – correlation coefficient.

The values of the standard deviation s were calculated with the use of the below formula (10):

$$s = \sqrt{\frac{\sum\left(x-\overline{x}\right)^2}{\left(n-1\right)}} \tag{10}$$

where:

x – result of measurement,

$\overline{x}$ – arithmetic average of measurement results

3. Results and discussion

The chemical composition of the analyzed steel is presented in Table 1.

TABLE 1

The chemical composition of the analyzed steel

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	B
0.20-0.30	0.94-1.40	0.14-0.34	0.015-0.025	0.007-0.020	0.40-0.57	0.42-0.55	0.20-0.26	0.10-0.19	0.002-0.004

Fatigue strength coefficient k was calculated to determine the bending fatigue strength of hardened steel tempered at 200, 300, 400, 500 and 600°C subject to the quotient of the diameter of impurities and the spacing between impurities. The results are presented respectively in Figure 1-5. The regression equation and the value of the correlation coefficient r are shown respectively in (11)-(15).

$$k_{(200)} = 3.8493\ \omega + 0.5833 \text{ and } r = 0.9309 \tag{11}$$

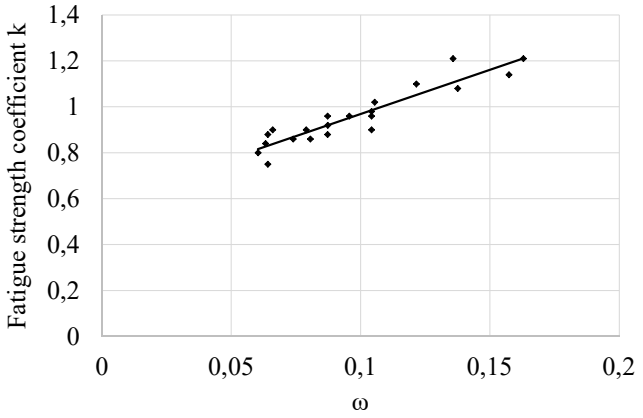

Fig. 1. Fatigue strength coefficient k of hardened steel tempered at 200°C subject the quotient of the diameter of impurities and the spacing between impurities ω

$$k_{(300)} = 2.5997\ \omega + 0.6501 \text{ and } r = 0.9303 \tag{12}$$

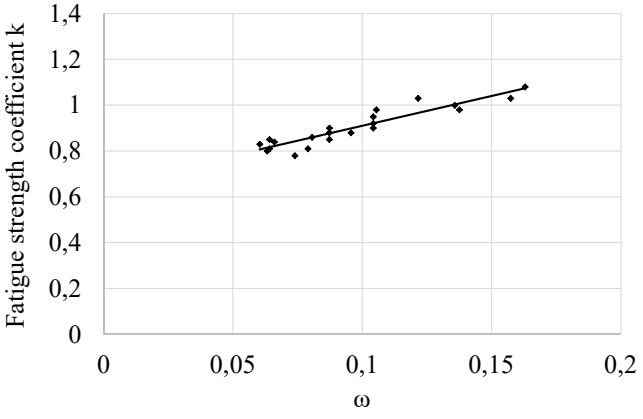

Fig. 2. Fatigue strength coefficient k of hardened steel tempered at 300°C subject the quotient of the diameter of impurities and the spacing between impurities ω

$$k_{(400)} = 3.49\ \omega + 0.5883 \text{ and } r = 0.9085 \quad (13)$$

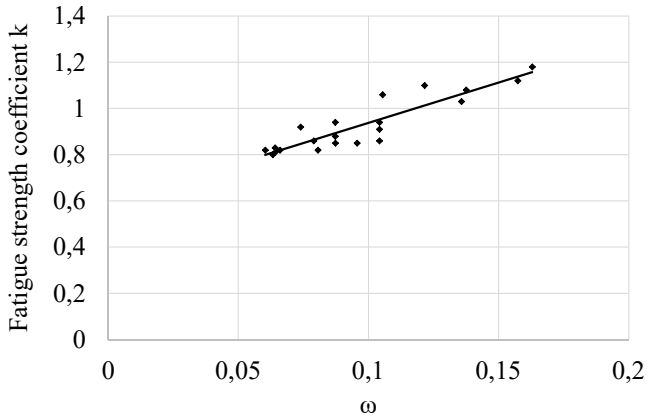

Fig. 3. Fatigue strength coefficient k of hardened steel tempered at 400°C subject the quotient of the diameter of impurities and the spacing between impurities ω

$$k_{(500)} = 2.1476\ \omega + 0.6838 \text{ and } r = 0.8471 \quad (14)$$

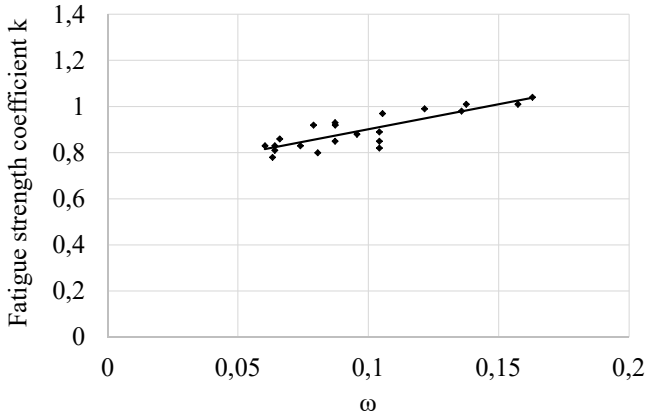

Fig. 4. Fatigue strength coefficient k of hardened steel tempered at 500°C subject the quotient of the diameter of impurities and the spacing between impurities ω

$$k_{(600)} = 3.096\ \omega + 0.6252 \text{ and } r = 0.9194 \quad (15)$$

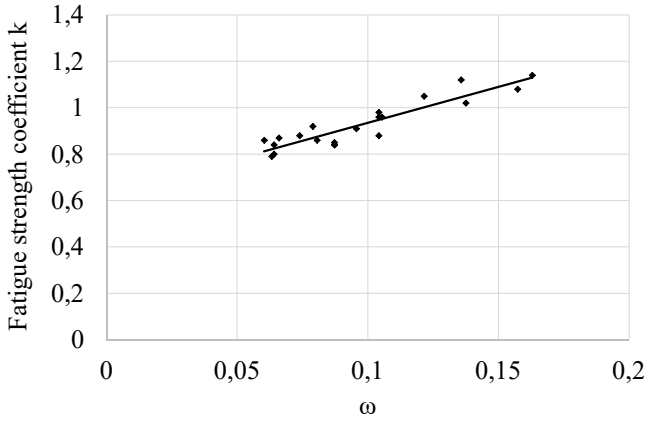

Fig. 5. Fatigue strength coefficient k of hardened steel tempered at 600°C subject the quotient of the diameter of impurities and the spacing between impurities ω

Fatigue strength coefficient k was calculated to determine the bending fatigue strength of hardened steel tempered at all analyzed temperatures subject to the quotient of the diameter of impurities and the spacing between impurities ω. The results are presented in Figure 6. The regression equation and the value of the correlation coefficient r are shown in (16).

$$k = 3.0419\ \omega + 0.6261 \text{ and } r = 0.8763 \quad (20)$$

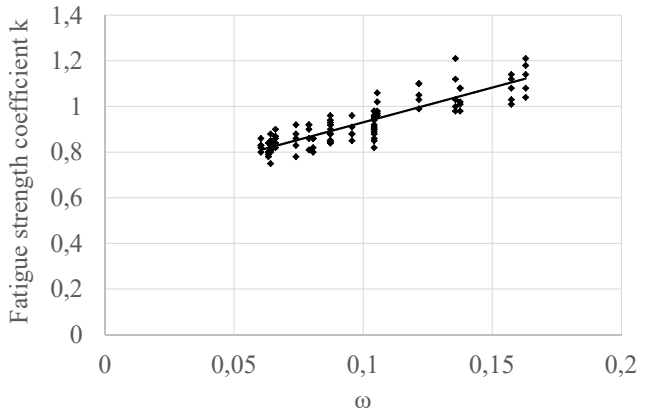

Fig. 6. Fatigue strength coefficient k of hardened steel tempered at all analyzed temperatures subject to the quotient of the diameter of impurities and the spacing between impurities ω

Relative volume of non-metallic inclusions V_0 in steel subject to the quotient of the diameter of impurities and the spacing between impurities ω are presented in Figure 7. The regression equation and the value of the correlation coefficient r are shown in (17).

$$V_0 = 0.5807\ \omega + 0.0041 \text{ and } r = 0.9997 \quad (17)$$

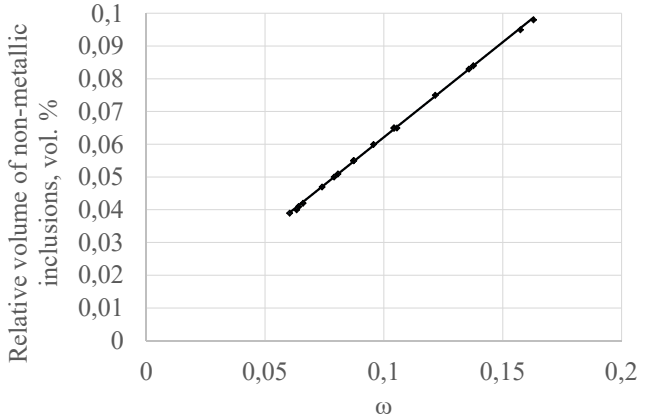

Fig. 7. Relative volume of non-metallic inclusions V_0 in steel subject to the quotient of the diameter of impurities and the spacing between impurities ω

The correlation coefficient in equation (17) $r = 0.9997$ is close to unity, therefore, the equation fits the described correlation. Thus, it can be assumed that:

$$\omega = \frac{V_0}{0.58} - 7 \cdot 10^{-3} \quad (18)$$

At each tempering temperature, coefficient k (11)-(16) changes linearly from 0.8 at $\omega \approx 0.06$ to 1.15 at $\omega \approx 0.16$. The mean values of $\overline{k}$ (Table 2), excluding the values for steel tempered at 200°C, are similar in the range of 0.90 and 0.93. An increase in deviation $\overline{k}$ from 0.9 was accompanied by an increase in standard deviation s_k. $\overline{\omega}$ was determined at 0.097, and its standard deviation at $s_\omega = 0.3$.

TABLE 2

Statistical parameters representing the results of the experiment

$t_{temp.}$, °C	$\overline{k}$	s_k	$\overline{\omega}$	s_ω
200	0.96	0.127	0.097	0.03
300	0.90	0.086		
400	0.93	0.118		
500	0.90	0.079		
600	0.93	0.104		
All	0.92	0.105		

In an analysis of regression equations (Table 3, Figs. 1-7) parameter a was determined in the range of 2.17-3.85, and parameter b – in the range of 0.58-0.68. Neither parameter was correlated with tempering temperature, correlation coefficient r or dissipation δ. All regression equations were characterized by a high correlation coefficient of around 0.9, which points to high statistical significance confirmed by Student's t-test. The above data indicate that the equations describing parameter k at different tempering temperatures, where $r = 0.88$, can be replaced with a single equation for all tempering temperatures (19).

$$k = 3\omega + 0.63 \tag{19}$$

Based on (18), equation (19) can also be expressed as (20):

$$k = 5.17 V_0 + 0.62 \tag{20}$$

Based on (3) and (19), the relationship between the fatigue strength and hardness of high-grade steel under rotary bending conditions vs. the quotient of the diameter of impurities and the spacing between impurities (21) can be written as follows:

$$z_{go} = (3\omega + 0.63) HV \tag{21}$$

and based on (18) and (21), the relationship between the fatigue strength and hardness of steel vs. the relative volume of submicroscopic non-metallic inclusions can be written as (22):

$$z_{go} = (5.17 V_0 + 0.62) HV \tag{22}$$

4. Conclusions

This study demonstrated correlations between the quotient of the diameter of impurities and the spacing between impurities, and the quotient of z_{go} and HV of non-metallic inclusions measuring up to 2 μm.

The proposed linear regression equations supported the determination of fatigue strength coefficient k with sufficient accuracy for every tempering temperature.

The single equation (19) for all tempering temperatures supports simpler calculation of parameters k (19 and 20) and z_{go} (21 and 22), but with a somewhat greater error (Table 2).

To estimate fatigue strength based on the results of non-destructive tests, coefficient k was introduced in equations (21) and (22) to determine fatigue strength as a function of hardness. The studies confirmed the effects of pollution on the properties of steel, too.

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TABLE 3

Parameters representing mathematical models (10 and 11) and correlation coefficients

Tempering temperature °C	Regression coefficient a (6) and (7)	Regression coefficient b (6) and (7)	Correlation coefficient r	Degree of dissipation k around regression line δ (9)	$t_{\alpha = 0.05}$ calculated by (8)	$t_{\alpha = 0.05}$ from Student's distribution for $p = (n - 2)$
200	3.8493	0.5833	0.9309	39.4496	11.1086	2.093
300	2.5997	0.6501	0.9303	22.0080	11.0553	
400	3.49	0.5833	0.9085	22.5658	9.4764	
500	2.1746	0.6838	0.8471	24.2334	6.9480	
600	3.096	0.6252	0.9194	17.9356	10.1890	
All	3.0419	0.6261	0.8763	21.9685	7.9285	1.983

All – arithmetic means of the analyzed parameters at all tempering temperatures.

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