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# THE EFFECT OF THE VOLUME OF INCLUSIONS ON THE FATIGUE STRENGTH COEFFICIENT OF STRUCTURAL STEEL

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The influence of impurities on fatigue strength has been researched extensively, but very few studies analyze the effect of impurities on the coefficient given by equation (1) which is used to estimate fatigue strength (zgo)based on Vickers hardness (HV), i.e. in non-destructive tests. Coefficient *k* is the quotient of fatigue strength $z_g$ divided by Vickers hardness HV.

The article discusses the results of a study investigating the effect of the percentage volume of non-metallic inclusions on the fatigue strength coefficient of structural steel during rotary bending. The study was performed on heats produced in an industrial plant. Fourteen heats were produced in an electric furnaces and oxygen converter. All heats were desulfurized. A half of heats from electrical furnaces were refined with argon, and heats from the converter were subjected to vacuum circulation degassing.

Steel were hardened and tempered at different temperatures. The results were presented graphically, and the fatigue strength coefficient of steel with a varied share of non-metallic inclusions was determined during rotary bending. The results revealed that fatigue strength coefficient is determined by the percentage volume of non-metallic inclusions and tempering temperature.

*Keywords: Steel, structural steel, non-metallic inclusions, fatigue strength, fatigue strength coefficient, bending* fatigue, bending pendulum

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## Introduction

High grade steel has a relatively small number of non-metallic inclusions. Despite this impurities have a considerable impact on the mechanical properties of steel in particular on fatigue strength [1,2]. 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 [3-6].

The strength of structural materials can also be assessed based on other tests that do not cause damage to the examined parts, such as hardness tests. Various indicators that support effective evaluation of the tensile strength of specific materials, subject to hardness, have been proposed in the literature ($R_m$ = c HV). Other correlations are used to estimate a material's fatigue strength based on its tensile strength ($z_{go}$ = e $R_m$). However, both approaches ($z_{go}$ and $R_m$) involve destructive tests. A better solution is to estimate fatigue strength (which is a costly and time-consuming test) based on a material's hardness, with the use of fatigue resistance coefficient *k* - the quotient of fatigue strength $z_{go}$ and Vickers hardness HV (1) [7,8].

$$k = \frac{z_{go}}{HV} \tag{1}$$

where $z_{go}$ is fatigue strength

The influence of impurities on fatigue strength has been researched extensively, but very few studies analyze the effect of impurities on the coefficient given by equation (1) which is used to estimate fatigue strength ($z_{go}$) based on Vickers hardness (HV), i.e. in non-destructive tests. Coefficient *k* is the quotient of fatigue strength $z_g$ divided by Vickers hardness HV.

The objective of this study was to determine the influence of non-metallic inclusions on the fatigue strength coefficient of structural steel with high plasticity.

## OBJECT AND METHODS

The tested material comprised low alloy structural steel manufactured in industrial processes. The resulting heats differed in purity and size of non-metallic inclusions. 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.

In the first process, steel was melted in a 140-ton basic arc furnace. The study was performed on 21 heats produced in an industrial plant. The metal was tapped into a ladle, it was desulfurized and 7-ton ingots were uphill teemed. Billets with a square section of 100x100 mm were rolled with the use of conventional methods. As part of the second procedure, steel was also melted in a 140-ton basic arc furnace. After tapping into a ladle, steel was additionally refined with argon. Gas was introduced through a porous brick, and the procedure was completed in 8-10 minutes. Steel was poured into moulds, and billets were rolled similarly as in the first method. In the third process, steel was melted in a 100-ton oxygen converter and deoxidized by vacuum. Steel was cast continuously and square 100x100 mm billets were rolled. 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.

The number of particles 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 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 [9].

It in aim of qualification of fatigue proprieties from every melting was taken 51 sections. The sections possessing the shapes of cylinder about diameter 10 mm. Their main axises be directed to direction of plastic processing simultaneously. It thermal processing was subjected in aim of differentiation of building of structural sample [9]. It depended on hardening from austenitizing by 30 minutes in temperature 880$^{o}$C after which it had followed quenching in water, for what was applied drawing. Tempering depended on warming by 120 minutes material in temperature 200, 300, 400, 500 or 600$^{o}$C and cooling down on 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. During heat treatment, steel sections were hardened and tempered at a temperature of 200, 300, 400, 500 and 600°C. 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.

Examination was realized on rotatory curving machine about frequency of pendulum cycles: 6000 periods on minute. For basis was accepted on fatigue defining endurance level $10^7$ 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$^0$C - 650 MPa,
- for steel tempered at a temperature of 300$^0$C - 500$^0$C - 600 MPa,
- for steel tempered at a temperature of 600$^0$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 [1,4].

The general form of the mathematical model is presented by equation (2)

$$k_{(\text{temp. tempered})} = a \cdot w + b \qquad (2)$$

where k – fatigue strength coefficient; w – relative volume of non-metallic inclusions, vol. %; a and 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 $\alpha$=0.05 and the number of degrees of freedom $f = n$-2 by formula (3).

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \tag{3}$$

The values of the diffusion coefficient $z_{go}$ near the regression line were calculated with the use of the below formula (4):

$$\delta = 2s_{zgo}\sqrt{1-r^2} \tag{4}$$

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

## 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 |

Examples of typical non-metallic inclusions in steel produced in every analyzed process are presented in [6]. Miain inclusions are: $Al_2O_3$ inclusions in the shape of irregular polyhedrons, small spherical MgO inclusions; spherical MgO inclusions and $Cr_2O_3$ parallelepiped inclusions, $SiO_2$·CaO·MnO multiphase inclusions.

Statistically significant relationship fatigue strength coefficient k as a function volume of non-metallic inclusions are shows in Figures 1-5.

The fatigue strength coefficient k of steel hardened and tempered at 200°C subject to percentage volume of inclusions are presented in Figure 1 and regression equation and correlation coefficients r at (5).

$$k(200) = 1.74 \cdot w + 0.69 \tag{5}$$

and r=0.7208

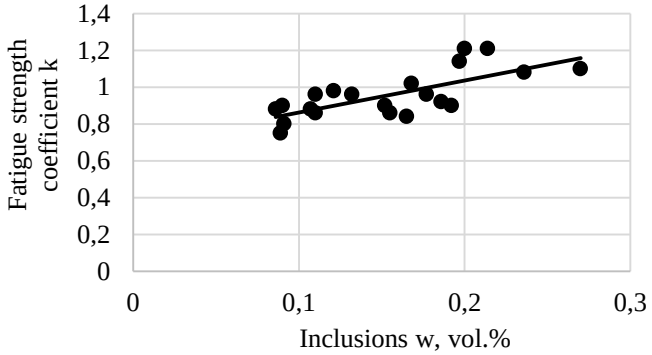


**Figure 1**. Fatigue strength coefficient of steel hardened and tempered at 200°C subject to percentage volume of inclusions.

The fatigue strength coefficient k of steel hardened and tempered at 300°C subject to percentage volume of inclusions are presented in Figure 2 and regression equation and correlation coefficients r at (6).

$$k(300) = 1.02 \cdot w + 0.75 \quad (6)$$

and r=0.7331

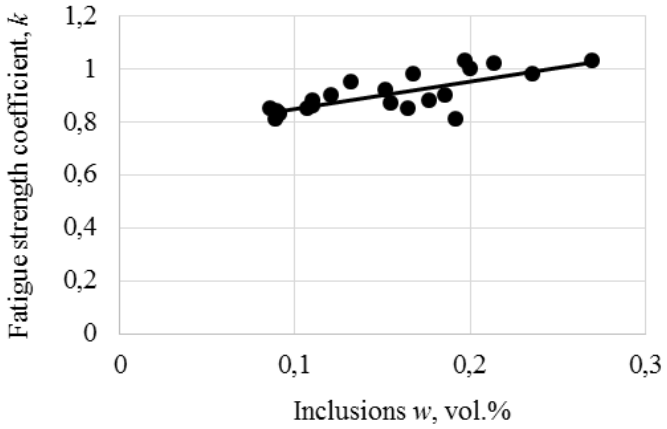


**Figure 2.** Fatigue strength coefficient of steel hardened and tempered at 300°C subject to percentage volume of inclusions.

The fatigue strength coefficient k of steel hardened and tempered at 400°C subject to percentage volume of inclusions are presented in Fig. 3 and regression equation and correlation coefficients r at (7).

$$k(400) = 1.71 \cdot w + 0.66 \quad (7)$$

and r=0.7616

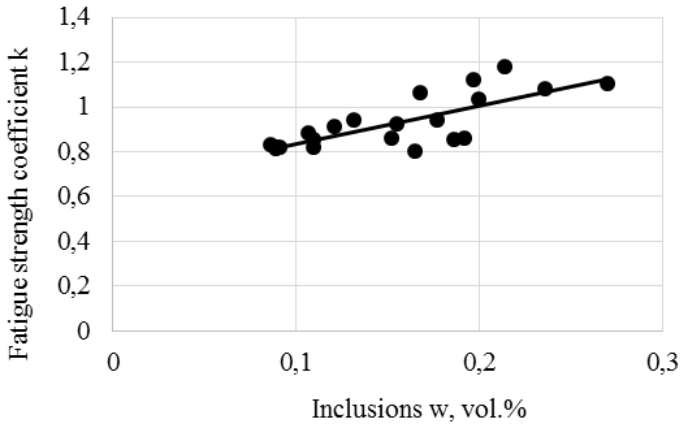


**Figure 3.** Fatigue strength coefficient of steel hardened and tempered at 400°C subject to percentage volume of inclusions.

The fatigue strength coefficient k of steel hardened and tempered at 500°C subject to percentage volume of inclusions are presented in Figure 4 and regression equation and correlation coefficients r at (8).

$$k(500) = 1.17 \cdot w + 0.72 \quad (8)$$

and r=0.7769

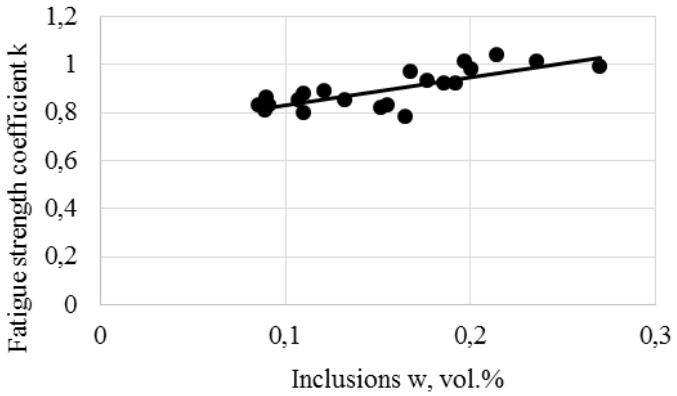


**Figure 4.** Fatigue strength coefficient of steel hardened and tempered at 500°C subject to percentage volume of inclusions.

The fatigue strength coefficient k of steel hardened and tempered at 600°C subject to percentage volume of inclusions are presented in Figure 5 and regression equation and correlation coefficients r at (9).

$$k(600) = 1.36 \cdot w + 0.73 \quad (9)$$

and r=0.7213

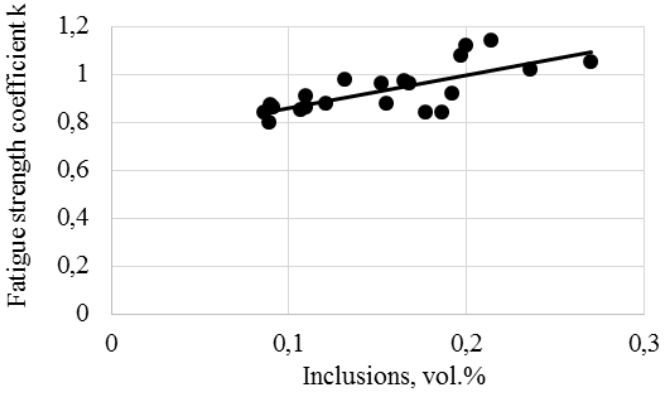


**Figure 5.** Fatigue strength coefficient of steel hardened and tempered at 600°C subject to percentage volume of inclusions.

For each of the analyzed regression equation was an increase in fatigue strength coefficient with the increasing percentage volume of inclusions. This is only possible for steel with a high purity. In steels of high purity non-metallic inclusions present inside the material can act as a lock for the developing microcracks. Of course, large or inclusions present in the outer layer (on the surface of the working element) can weaken the tested coefficient.

**Table 2.** Parameters representing mathematical models (10 and 11) and correlation coefficients

| Tempering temperature $^{o}$C | Regression coefficient a (2) | Regression coefficient b (2) | Correlation coefficient r | Degree of dissipation k around regression line δ (4) | $t_{\alpha=0.05}$ calculated by (3) | $t_{\alpha=0.05}$ from Student's distribution for p=(n-2) |
|---|---|---|---|---|---|---|
| 200 | 1.7411 | 0.6883 | 0.7208 | 0.17605835 | 4.53282208 | 2.093 |
| 300 | 1.0238 | 0.7843 | 0.7331 | 0.11698079 | 4.69844256 | |
| 400 | 1.7093 | 0.6633 | 0.7616 | 0.15293919 | 5.12267684 | |
| 500 | 1.1653 | 0.7150 | 0.7769 | 0.09948059 | 5.37849344 | |
| 600 | 1.3580 | 0.5203 | 0.7213 | 0.14406554 | 4.53937398 | |

In an analysis of regression equations (Table 2, Figure 1-5) parameter *a* was determined in the range from 1.02 for tempering temperature 300$^{o}$C to 1.74 for 200$^{o}$C, and parameter *b* – in the range from 0.52 for 500$^{o}$C to 0.78 for 300$^{o}$C. Neither parameter was correlated with tempering temperature, correlation coefficient *r* or dissipation $\delta$. All regression equations were characterized by a high correlation coefficient of over 0.7, which points to high statistical significance confirmed by Student's t-test.

## CONCLUSIONS

1. The proposed linear regression equations supported the determination of fatigue strength coefficient *k* with sufficient accuracy for every tempering temperature for high purity steels.
2. The regression equations (5) - (9), despite the fact that the present data from three different manufacturing processes depict a statistically significant relationship between the percentage volume of inclusions (separately for each of the melts) and Fatigue strength coefficient.
3. Analyzing the correlation coefficient r for each tempering temperature was found strength relationships of the analyzed functions on the same level (about 0.7).

## REFERENCES


[1] T.Y.Shish, T.Araki. The effect of non metallic inclusion and microstructures on the fatigue crack initiation and propagation in high strength carbon steel.Trans.Iron. Steel Inst.Jap. 1973, 1, 11-19p.

[2] C.W.Anderson, G.Shi, H.V.Atkinson,C.M.Sellars. The precision of methods using the statistics of extremes for the estimation of the maximum size of inclusions in clean steels, Acta Materialia, 2000, 48(17), 4235-4246p.

[3] M.A.Miner. Cumulative damage in fatigue. Trans. ASM 1945, 65, 159-165p.

[4] Kocańda, S. 1985. Zmęczeniowe pękanie metali, WNT Warsaw (in Polish).

[5] B.Pyttel, D.Schwerdt, C.Berger. Very high cycle fatigue – Is there a fatigue limit? International Journal of Fatigue, 2011, 33, 49–58p.

[6] T.Lipiński, A.Wach. The effect of the production process of medium-carbon steel on fatigue strength, Archives of Foundry Engineering, 2010, 10(2) 79-82p.

[7] S.Kocańda, J. Szala. 1985. Basis of fatigue calculation. PWN Warsaw (in Polish).

[8] T.Lipiński. The influence of the distribution of nonmetallic inclusion on the fatigue strength coefficient of high purity steels. Journal of Achievements of Materials and Manufacturing Engineering 2015, 69(1), 18-25p.

[9] J.Ryś. 1995. Stereology of materials. FOTOBIT DESIGN, Krakow (in Polish).



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