



Influence of inclusions on bending fatigue strength coefficient the medium carbon steel melted in an electric furnace

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Abstract

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. The analyzed material was one grade of medium-carbon structural steel. The study was performed on 6 heats produced in an industrial plant in 140 ton electric furnaces. The experimental variants were compared in view of the five heat treatment options. The results were presented to account for the correlations between the fatigue strength coefficient during rotary bending, the diameter of and spacing between impurities. 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 was determined. The proposed equations contribute to the existing knowledge base of practices impact of impurities with various diameters and spacing between non-metallic inclusion on fatigue strength.

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1. Introduction

When designing parts of machine parts, it is necessary to ensure quality that guarantees reliable operation of the device during its lifetime (Selejdak et al., 2014; Ulewicz et al., 2013b). To achieve this goal, it is required to conduct experimental research and reduce the testing costs by computer simulations (Pietraszek et al., 2014; Ulewicz et al., 2013a). In order to reduce the costs of testing, they are usually conducted on a laboratory scale (Majewski et al., 2020; Pietraszek et al., 2015). For this reason, tests performed in industrial conditions are extremely important. The most harmful in processes of exploitation are damages and breakdowns of machines. They are usually random and unforeseeable. The reasons of breakdown can be different. As early as from human factor, and having finished on constructional or material factor (Radek et al. 2017; Ulewicz et al., 2016; Wrońska et al., 2019). The most common cause of damage during operation is damage due to material fatigue (Ejaz et al., 2010; Ulewicz et al., 2017; Fernandes et al., 2003; Genal 2005).

The quality of material in fatigue strength is the essential question. The impurity content is also a key determinant of

the quality of high-grade steel. As regards steel, non-metallic inclusions have mostly a negative effect which is dependent on their content, size, shape and distribution (Atkinson et al., 2003; Zhang et al. 2005; Kasatkin 2004). The quantity and quality of non-metallic inclusions is determined mostly by the steel melting technology (Anderson et al., 2002; Lipiński et al., 2009, 2010; Girovic-Gekic et al., 2009; Murakami et al., 1994). Outfurnace treatment regimes are also introduced to minimize the quantity of non-metallic inclusions. Non-metallic inclusions may be introduced to liquid steel from the outside, usually with charge material, or they may be produced in the metallurgical process. Non-metallic inclusions in steel may be classified into two groups endogenous – including sulfides, oxides and silicates produced in liquid steel during the metallurgical process, exogenous – mostly particles of refractory lining material in furnaces, tapping spouts and ladles which penetrate liquid steel from the outside (Steiner et al., 2003; Lipiński et al., 2014; Lipiński et al., 2015; Moiseeva et al., 2007; Kissling et al., 1978, Ulewicz et al. 2014).

Burdens of variables resistance depend not only from level of strains. It depends on state of matter also, and particularly structure of metallic phase of its physical proprieties and strength, as well as from non-metallic inclusions being in steel as a pollution (Yang et al., 2006; Lipiński et al., 2015; Zhang et al. 2007; Dekkkers 2002). The influence of impurities on fatigue strength has been researched extensively, but very few studies analyze the effect of impurities, fatigue strength and hardness simultaneously. In this study, attempts were made to analyze the impact of impurities with various diameters and spacing between non-metallic inclusion on fatigue strength coefficient determined under rotary bending fatigue strength of high purity steels produced in electric furnace an industrial plant.

2. Experimental

Steel was melted in a 140-ton basic arc furnace. The study was performed on 6 heats produced in an industrial plant. The metal was tapped into a ladle, it was desulfurized and 7-ton ingots were uphill teemed. Steel was poured into moulds. 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. Relative volume of non-metallic inclusions were determine by inspecting metallographic specimens with the use of a Quantimet video inspection microscope under 400x magnification. It was determined for a larger boundary value of 2 μm . 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 analyzed sections had a cylindrical shape and a diameter of 10 mm with main axes were oriented in the direction of processing. The sections were thermally processed to determine differences in their microstructural 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. Heat treatments were selected to produce heats with different microstructure of steel, from hard microstructure of tempered martensite, through sorbitol to the ductile microstructure obtained by spheroidization. The application of various heat treatment parameters led to the formation of different microstructures responsible for steel hardness values in the following range from 249 to 438 HV (Wach 2010).

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.

The arithmetic average size proportions and distances between the impurities of structural steel α were calculated with the use of the below formula (1):

$$\alpha = \frac{d}{\lambda} \quad (1)$$

where:

d – average diameter of impurity (μm)

λ - arithmetic average distance between impurities (μm).

The arithmetic average distances between impurities for each of the heats λ were calculated with the use of the below formula (2):

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

where:

d – average diameter of impurity (μm),

V – relative volume of submicroscopic impurities (%).

Coefficient k is the quotient of fatigue strength zg divided by Vickers hardness HV (3).

$$k = zg/HV \quad (3)$$

where:

zg – fatigue strength (MPa),

HV – Vickers hardness (HV).

The presence of statistically significant correlations was verified by Student's t-test on $\alpha=0.05$.

3. Results and discussion

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

Table 1. average chemical composition of the analyzed steel

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	B
0.26	1.19	0.22	0.02	0.01	0.52	0.50	0.25	0.16	0.003

Fatigue strength coefficient k of hardened steel tempered at 200, 300, 400, 500, 600°C and all five tempered temperature subject the quotient of the diameter of impurities and the spacing between impurities α are presented respectively in Figure 1-6. The regression equation and the value of the correlation coefficient r are shown respectively in (4)-(9).

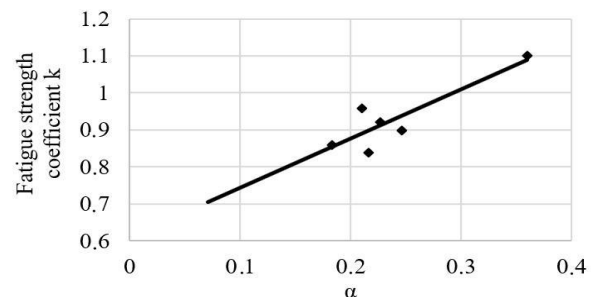


Fig. 1. Fatigue strength coefficient k of hardened steel tempered at 200°C subject the quotient of the diameter of impurities and the spacing between impurities α

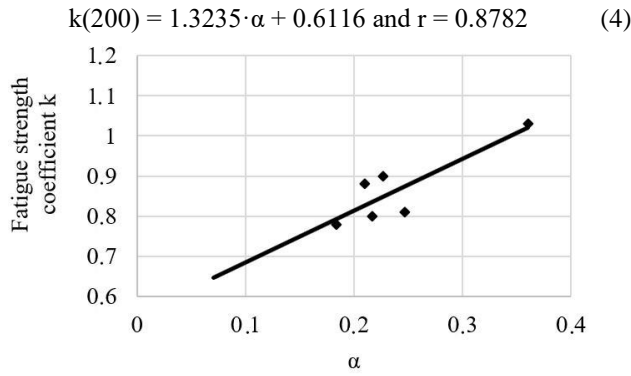


Fig. 2. Fatigue strength coefficient k of hardened steel tempered at 300°C subject the quotient of the diameter of impurities and the spacing between impurities α

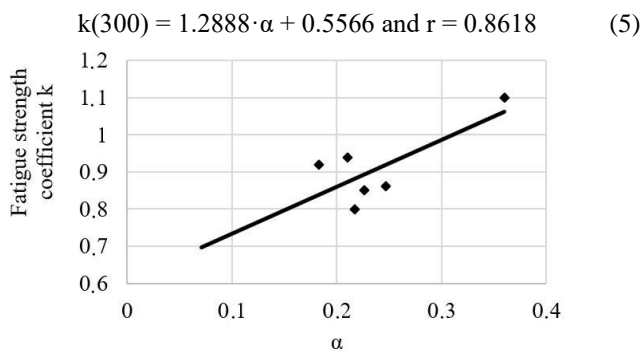


Fig. 3. Fatigue strength coefficient k of hardened steel tempered at 400°C subject the quotient of the diameter of impurities and the spacing between impurities α

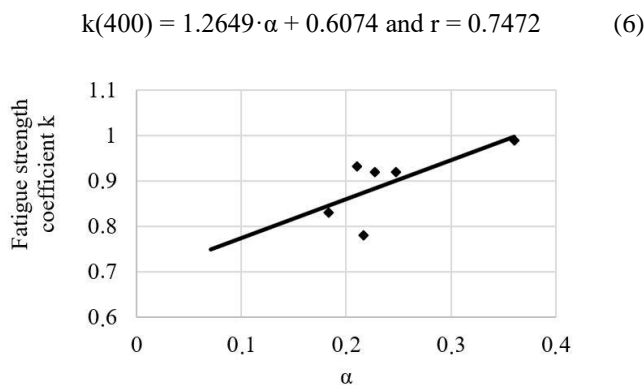


Fig. 4. Fatigue strength coefficient k of hardened steel tempered at 500°C subject the quotient of the diameter of impurities and the spacing between impurities α

$k(500) = 0.8601 \cdot \alpha + 0.6881$ and $r = 0.7021$ (7)

Diameter of impurities divided by spacing between impurities (α) of structural steel for all tempering temperatures, takes values from 0.18 to 0.36.

Fatigue strength coefficient k of hardened medium carbon structural steel tempered at different temperatures is in the range of 0.78 to 1.1. Its values above unity were recorded for $\alpha = 0.36$ only. Its largest spread was noted for the tempering temperature of 400°C (microstructure of sorbitol) Figure 3,

and not the lowest for 200°C (tempered martensite hard microstructure) Figure 1.

As the diameter of impurities divided by spacing between impurities (α) increased, k increased for all tempering temperatures. This may confirm that large inclusions and short distances between them reduce the fatigue strength of steel.

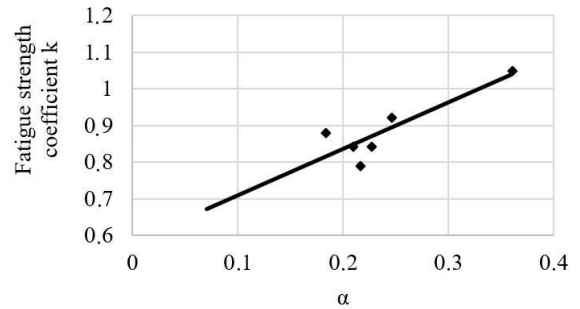


Fig. 5. Fatigue strength coefficient k of hardened steel tempered at 600°C subject the quotient of the diameter of impurities and the spacing between impurities α

$k(600) = 1.2709 \cdot \alpha + 0.5809$ and $r = 0.8661$ (8)

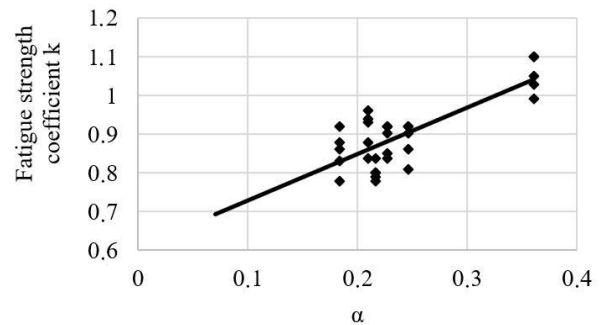


Fig. 6. Fatigue strength coefficient k of hardened steel tempered at 200, 300, 400, 500 and 600°C subject the quotient of the diameter of impurities and the spacing between impurities α

$k(\text{all}) = 1.2017 \cdot \alpha + 0.6089$ and $r = 0.7838$ (9)

4. Conclusion

Based on the results of the research, it was found that:

- there are correlations between the diameter of non-metallic inclusions divided by spacing between impurities and the bending fatigue coefficient for different range of tempering temperature,
- the coefficient k allows for estimating fatigue strength in relation to diameter of impurities and the spacing between impurities and can be used to simulate steel fatigue strength,
- along with the increase in α parameter, an increase in coefficient k was noted for all tempering temperatures. This confirms that for large inclusions and small distances between them, decreases the fatigue strength of steel.

Reference

- Anderson, C.W., Coles S.G., 2002. *The largest inclusions in a piece of steel*, *Extremes*, 5, 237-252.
- Atkinson, H.V., Shi, G., 2003. *Characterization of inclusions in clean steels: a review including the statistics of extremes methods*, *Progress in Materials Science*, 48, 457-520.
- Dekkers, R., 2002. *Thesis, Katholieke Universiteit Leuven*, Ph.D., Leuven, Belgium.
- Ejaz, N., Rizvi, S.A., 2010. *Cable failure resulted in the crash of a trainer aircraft*, *Engineering Failure Analysis*, 17, 394-402.
- Fernandes, M., Pires, J.C., Cheung, N., Garcia, A., 2003. *Influence of refining time on nonmetallic inclusions in a low-carbon, silicon-killed steel*, *Materials Characterization*, 51, 301-308.
- Genel, K., 2005. *Estimation method for the fatigue limit of case hardened steels*, *Surface & Coatings Technology*, 194, 9591-9592.
- Gigovic-Gekic, A., Oruc, M., Vitez, I., Vujicic B., 2009. *Analyse and re-search of nonmetallic inclusions for steel 100Cr6*, *Metallurgija*, 48, 1, 29-32.
- Kasatkin, G.N., 2004. *Effect of nonmetallic inclusions on the mechanical properties of hydrogenated steels*, *Materials Science*, 40/6, 850-855.
- Kiessling, R., 1978. *Non-metallic inclusions in steel*, The Institute of Materials, London, UK.
- Lipiński, T., Wach, A., 2009. *Non-metallic inclusions structure dimension in high quality steel with medium carbon contents*, *Archives of Foundry Engineering*, 9(3), 75-78.
- Lipiński, T., Wach, A., 2010. *The effect of the production process of medium-carbon steel on fatigue strength*, *Archives of Foundry Engineering*, 10(2), 79-82.
- Lipiński, T., Wach, A., 2014. *Size of Non-Metallic Inclusions in High-Grade Medium Carbon Steel*, *Archives of Foundry Engineering*, 14(4), 55-60.
- Lipiński, T., Wach, A., 2015. *Effect of impurities on bending fatigue strength of structural steel*, *Engineering for Rural Development*, 784-789.
- Lipiński, T., Wach, A., 2015. *The Effect of Fine Non-Metallic Inclusions on The Fatigue Strength of Structural Steel*, *Archives of Metallurgy and Materials*, 60(1), 65-69.
- Majewski, G., Orman, Ł.J., Telejko, M., Radek, N., Pietraszek, J., Dudek A., 2020. *Assessment of thermal comfort in the intelligent buildings in view of providing high quality indoor environment*, *Energies* 13(8), 1973.
- Moiseeva, L.A., Moiseev, B.P., 2007. *Composition, Structure, and Sources of Exogenous Inclusions in Steel*, *Steel in Translation*, 37(7), 607-613.
- Murakami, Y., Endo, M., 1994. *Effects of defects, inclusions and inhomogeneities on fatigue strength*, *Int J Fatigue*, 16(3), 163-82.
- Pietraszek, J., Gądek-Moszczak, A., Radek, N., 2015. *The estimation of accuracy for the neural network approximation in the case of sintered metal properties*, *Recent Developments in Computational Collective Intelligence*, 125-134.
- Pietraszek, J., Skrzypczak-Pietraszek, E., 2014. *The Optimization of the Technological Process with the Fuzzy Regression*, *Advanced Materials Research*, 874, 151-155.
- Radek, N., Broncek, J., Fabian, P., Pietraszek, J., Dudek A., 2017. *Tribological properties of electro-spark deposited coatings after laser treatment*, *Proc. 58th Int. Conf. Machine Design Departments (ICMD 2017)*, 129, 314-319.
- Selejdak, J., Ulewicz, R., Ingaldi M., 2014. *The evaluation of the use of a device for producing metal elements applied in civil engineering*, in *Chosen Metallurgical Company, 25th International Conference on Metallurgy and Materials*, Ostrava, Tanger, 1882-1888.
- Steiner, D., Petrovic, M., Jenko, M., Hraes, M., 2003. *Study of the morphology of non-metallic inclusions in non-oriented electrical steel containing Cu and Se*, *Vacuum* 71, 33-40.
- Ulewicz, R., Novy, F. 2017. *Fatigue life of high strength steel for cold forming*, *Metallurgija* 56(1-2), 115-118.
- Ulewicz, R., Mazur, M., 2013. *Fatigue testing structural steel as a factor of safety of technical facilities maintenance*, *Production Engineering Archives*, 1(1), 32-34.
- Ulewicz, R., Mazur, M., Bokůvka, O., 2013. *Structure and mechanical properties of fine-grained steels*, *Periodica Polytechnica Transportation Engineering*, 41(2), 111-115.
- Ulewicz, R., Novy, F., 2016. *The influence of the surface condition on the fatigue properties of structural steel*, *Journal of the Balkan Tribological association*, 22(2), 1147-1155.
- Ulewicz, R., Nový, F., Selejdak, J. *Advanced Materials Research*, 874, 43-48
- Wach, A., 2010. *Impact of secondary metallurgy on some properties of structural steel used on machine parts*, Ph.D. thesis, Olsztyn.
- Wrońska, A., Andres, J., Altamer, T., Dudek, A., Ulewicz, R., 2019. *Effect of Tool Pin Length on Microstructure and Mechanical Strength of the FSW Joints of Al 7075 Metal Sheets*, *Communications-Scientific letters of the University of Zilina*, 21(3), 40-47.
- Yang Z.G., Zhang, J.M., Li, S.X., Li, G.Y., Wang, Q.Y., Hui, W.J., Weng, Y.Q., 2006. *On the critical inclusion size of high strength steels under ultra-high cycle fatigue*, *Materials Science and Engineering, A* 427, 167-174.
- Zhang, J.M., Zhanga, J.F., Yang, Z.G., Li, G.Y., Yao, G., Li, S.X., Hui, W.J., Weng, Y.Q., 2005. *Estimation of maximum inclusion size and fatigue strength in high-strength ADF1 steel*, *Materials Science and Engineering A* 394, 126-131.
- Zhang, J.M., Li, S.X., Yang, Z.G., Li, G.Y., Hui, W.J., Weng, Y.Q., 2007. *Influence of inclusion size on fatigue behavior of high strength steels in the gigacycle fatigue regime*, *International Journal of Fatigue*, 29, 765-771.

夹杂物对电炉中熔碳钢的弯曲疲劳强度系数的影响

關鍵詞

结构钢
非金属夹杂物
氧化物杂质
疲劳强度
弯曲疲劳

摘要

优质钢的参数受多种因素影响，包括化学成分和生产工艺。杂质含量也是决定优质钢质量的关键因素。夹杂物的类型和形状也可能起重要作用。夹杂物可以通过抑制微裂纹的发展来提高钢的强度。被分析的材料是一种中碳结构钢。该研究是在 140 吨电炉的工业工厂中产生的 6 种热量下进行的。考虑到五个热处理选项，比较了实验变体。给出结果以说明旋转弯曲期间的疲劳强度系数，杂质的直径和间距之间的相关性。确定了高级钢的疲劳强度和硬度与杂质直径和杂质间距之间的关系。所提出的方程有助于实践中各种直径的杂质以及非金属夹杂物之间的间距对疲劳强度的影响。