INFLUENCE OF OXYGEN CONTENT IN MEDIUM CARBON STEEL ON BENDING FATIGUE STRENGTH

Tomasz Lipinski[1], Jacek Pietraszek[2], Anna Wach[1]
[1]University of Warmia and Mazury in Olsztyn, Poland;
[2]Cracow University of Technology, Poland

Abstract. Commercial iron alloys apart of typical chemical elements contain phosphorus, sulfur, oxygen as well as non-metallic inclusions. These elements can form solutions in liquid metal, or they can form separate phases. 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. Inclusions as impurities found in steel can affect its performance characteristics. The article discusses the results of a study investigating the effect of oxygen on the fatigue strength of structural steel during rotary bending. The study was performed on 7 heats produced in an industrial plant. Fourteen heats were produced in 100 ton oxygen converter. All heats were desulfurized. The heats from the converter were subjected to vacuum circulation degassing. The experimental variants were compared in view of the heat treatment options. The examination was realized by the rotatory curving machine about the frequency of pendulum cycles: 6000 periods on minute. For basis was accepted on fatigue defining endurance level 107 cycles. The level of the fatigue-inducing load was adapted to the strength properties of steel from 540 to 650 MPa. The fatigue strength of steel with tested for oxygen content in steel was determined during rotary bending. The results revealed that fatigue strength is determined by the contents of oxygen impurity spaces and tempering temperature. A reduction in the fatigue strength during rotary bending of low-carbon steel from 368 to 252 MPa was observed when the tempering temperature changed from 200 to 600oC. It was found that with an increase in the content from 0.0023%, 0.003% of the bending transfer (for all temperatures from 298 to 328 MPa) can be transferred.

Keywords: steel, structural steel, fatigue strength, bending fatigue, impurities.

Introduction

The existing now rapid technological progress and the demand for increasing highly reliable machines and devices spur research investigating the fatigue strength of structural materials. According to the presented research results in order to improve the fatigue life of steels, an effective measure is to decrease the volume fraction and the size of nonmetallic inclusion in steels. However, in a material with a plastic matrix, some of the small non-metallic recesses not only do not deteriorate the strength of the steel but even increase its durability. Fatigue testing is one of the most rigorous methods for determining the durability of a material. The analysis of the fatigue strength parameters as well as the distribution, quantity and quality of impurities present in the steel confirms that submicroscopic inclusions occurring in steels with high plasticity inhibit dislocation movement [1-11].

Commercial iron alloys with carbon contain sulfur, phosphorus, oxygen, and other impurities. These elements form solutions in liquid metal or form foreign phases. Non-metallic phases, also known as metallic inclusions or impurities, are formed during the course of the physicochemical reactions accompanying the metallurgical process. The amount of non-metallic inclusions is closely related to the content of undesirable components in the liquid alloy, including sulfur, phosphorus, oxygen and others. And their quality and morphology result from a specific metallurgical process of steel production. Non-metallic inclusions can also be solid particles that accidentally enter the alloy, e.g., ceramics from the furnace lining, impurities introduced with scrap, etc. [12-14].

Low carbon non-metals are multiphase. Their microstructure consists of various phases in the form of grains. The size of these grains depends on the manufacturing process. In their original form, their size depends on the cooling rate, and the geometric system depends on the parameters related to the distribution of heat dissipation. The grains are not perfectly matched to each other. Their random size and geometric shape compensate for grain boundaries, often with notched phases. The grain boundaries usually have different properties as compared to the grains. The result of this mismatch may also be the reduction of steel properties by the occurrence of discontinuities at the interfaces of various phases [15-21]. Non-metallic contaminants are commonly considered to be detrimental to fatigue strength, mainly of low plasticity steels [22-28]. Despite efforts, their complete elimination is impossible. Non-metallic inclusions formed in the metallurgical process constitute the main group of impurities in steel [29-31]. The impact of pollutants results from their quality, quantity and morphology [3; 12; 15; 32]. Therefore, the quality of high-purity steels depends on the chemical composition and technology of the production process [29-38]. Despite the high popularity of low carbon steels, the number of studies describing their fatigue strength is small. Many more works describe steels with a hard matrix, e.g., bearing [23; 25]. This is probably due to the easier-to-perform analysis. It should be emphasized that the mechanism of action of the non-metallic inclusion in the matrix made of plastic material differs from the analogous mechanism for the rigid matrix. This observation is also an incentive to take up this research topic.

The issues and conclusions contained in this article may be of interest to both researchers-practitioners in the field of materials science [39-43], related management [44; 45], and researchers involved in the implementation of new methods of data analysis [46; 47]. The aim of this study was to determine the influence of oxygen on the fatigue strength of high plasticity low carbon steel.

Materials and methods

The tested material was made of high-purity semi-finished products. It contained a low carbon content and additives with boron, chromium, manganese, molybdenum and nickel. Low content of sulfur and phosphorus as impurities was also present. The real average chemical composition of the 7 analyzed heats melted in the oxygen converter is 0.24% C, 0.003% B, 0.52% Ni, 1.17% Mn, 0.52% Cr, 0.24% Mo, 0.24% Si, 0.016% S, 0.017% P, 0.002% Cu and 0.003% O.

The experimental material obtained in industrial production consisted of structural steel obtained in 100-ton oxygen converter with vacuum degassed of steel. Billets with a square section of 100x100 mm were rolled with the use of conventional methods. With the aim of qualification of fatigue proprieties from every melting samples were taken on cylinder sections about the diameter 10 mm. Their main axis be directed to the direction of plastic processing simultaneously.

The content of alloy constituents was estimated with the use of LECO quantometer and conventional analytical methods.

After cutting and preparation, samples were austenitized at the temperature of 880 ºC for 30 minutes and then cooled in water. Immediately after quenching, the samples were tempered at the following temperatures: 200, 300, 400, 500 and 600 ºC, depending on the treatment variant, for 120 minutes and then cooled in air. The bending fatigue test was carried out on a 6000 rpm rotary bending machine. The load during the test was adapted to the mechanical properties of tested steels represented by tempering temperature: 200 ºC (650 MPa), 300-500 ºC (600 MPa), 600 ºC (540 MPa) [6; 13; 17].

Oxide inclusion of non-metallic Al_2O_3 constituted the main fraction of impurities constituting on average about 40%. SiO_2 was the second largest fraction by volume – on average about 15%. The remaining pollutants were (decreasingly in relation to the share): MnO, MgO, CaO, FeO and Cr_2O_3. The content of particles in steel after outside furnance treatment is presented in [38], the structure size and the analysis of their morphology in [30; 38].

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.

The critical value $t_{\alpha = 0.05}$ from the Student's distribution for $p = (n$-2) for tempered temperature: 200, 300, 400, 500 and 600 ºC is 2.447 and for all tempering temperatures is 1.980. The error of measuring physical quantities did not exceed 5%.

Results and discussion

The bending fatigue strength tested with rotary bending tested steel after hardened and tempered at: 200° subject to oxygen contents is presented in Fig. 1 and its regression equation and correlation coefficients r at (1), for tempered at 300 ºC are presented in Fig. 2 and its regression equation and correlation coefficients r at (2), for tempered at 400 ºC are presented in Fig. 3, and its regression equation and correlation coefficients r at (3), for tempered at 500 ºC are presented in Fig. 4, and its regression equation and correlation coefficients r at (4), for tempered at 600 ºC are presented in Fig. 5 and its regression equation and correlation coefficients r at (5). Based on the analysis of the results, it was found that the analysed relationships can be presented with a linear function. The analysis of statistical parameters confirms that the fatigue strength depends on the oxygen content in the alloy for steel subjected to tempering at the following temperatures: 300, 400, 500 and 600 ºC. These dependencies have an independent distribution and can be tested with functions of mathematical statistics. $t_\alpha = 0.05$ calculated for 200 ºC tempering temperature is 2.373 and $t_{\alpha = 0.05}$ from the Student's distribution for $p = (n$-1) is 2.447. Thus, the equation (1) is not statistically significant at the level of $a = 0.005$.

Analyzing the mathematical adjustments of the regression equations for individual tempering temperatures, an increase in the correlation coefficient r was found with an increase in the tempering temperature (respectively (2)-(5): 0.6545 for 300 ºC, 0.7106 for 400 ºC, 0.775 for 500 ºC and 0.7885 for 600 ºC). As the tempering temperature increases, the steel becomes more and more ductile. Thus, the role of the matrix with regard to the detachment of the oxygen content changes depending on the plasticity of the matrix of the oxide precipitates.

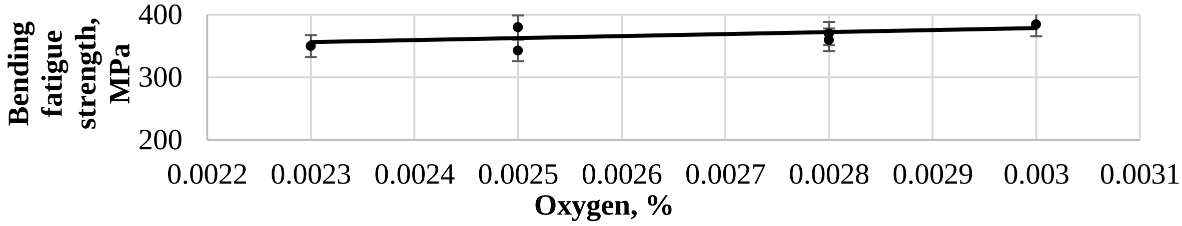

Fig. 1. **Bending fatigue strength of steel hardened from 880 ºC and tempered at 200 ºC subject to oxygen contents**

$$z_{go(200)} = 31976 \cdot O + 282.81, \; r = 0.4781 \tag{1}$$

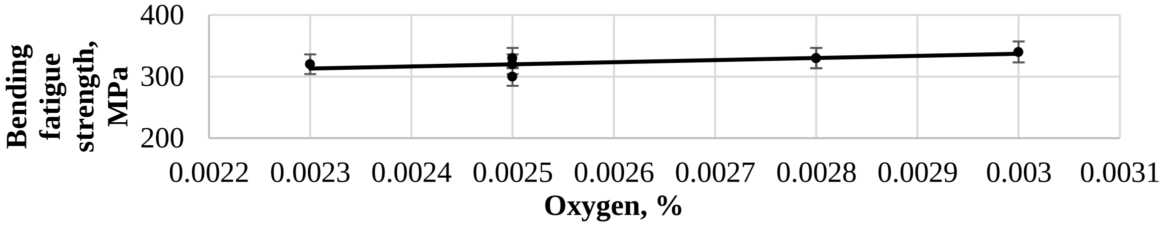

Fig. 2. **Bending fatigue strength of steel hardened from 880 ºC and tempered at 300 ºC subject to oxygen contents**

$$z_{go(300)} = 34274 \cdot O + 234.19, \; r = 0.6545 \tag{2}$$

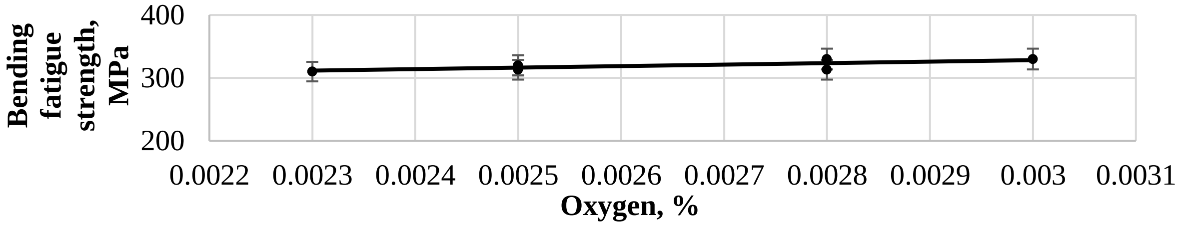

Fig. 3. **Bending fatigue strength of steel hardened from 880 ºC and tempered at 400 ºC subject to oxygen contents**

$$z_{go(400)} = 23750 \cdot O + 257, \; r = 0.7106 \tag{3}$$

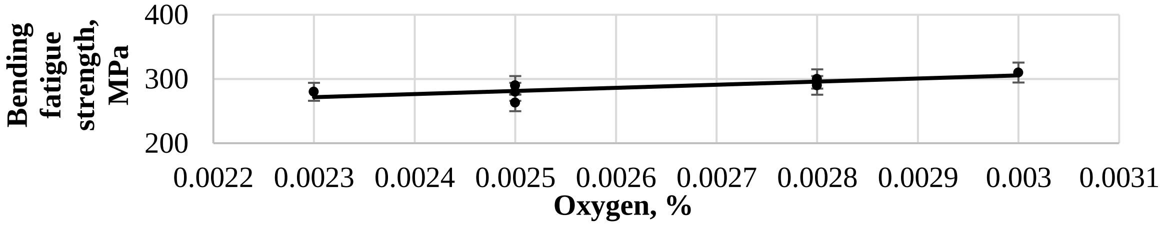

Fig. 4. **Bending fatigue strength of steel hardened from 880 ºC and tempered at 500 ºC subject to oxygen contents**

$$z_{go(500)} = 48508 \cdot O + 160.06, \; r = 0.7750 \tag{4}$$

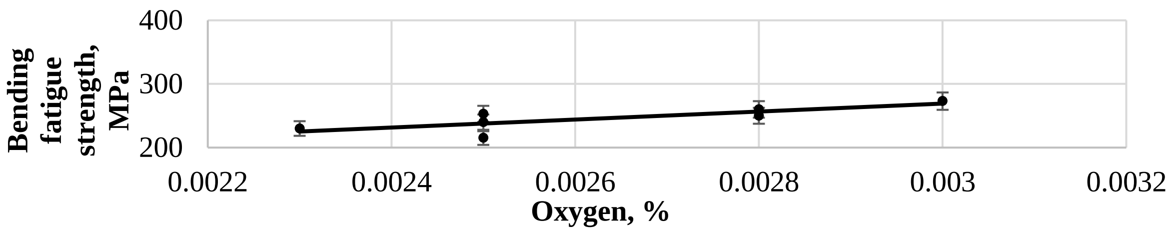

Fig. 5. **Bending fatigue strength of steel hardened from 880 ºC and tempered at 600 ºC subject to oxygen contents**

$$z_{go(600)} = 62742 \cdot O + 80.935,\ r = 0.7885 \quad (5)$$

The effect of oxygen on the bending fatigue strength is described with greater accuracy for steel tempered at higher temperatures, and therefore with a matrix having lower hardness and at the same time greater plasticity. An increase in the correlation coefficient was also observed with an increase in the tempering temperature of the steel. The obtained results of the research on the influence of oxygen on the fatigue strength are confirmed by other works [24]. The slope "a" determines the slope of the graph of the linear function to the axis representing the oxygen content. In Figs. 2-5 (statistically significant equations) the slope coefficients are high (from 23750 for tempered at 400 ºC to 62472 for tempered at 600 ºC), which indicates a significant angle of inclination of the linear function to the oxygen axis, and therefore relatively large changes in the bending fatigue strength depending on the oxygen content in steel. The fairly flat characteristics of the curves in the graph are due to the wide range of the bending fatigue strength axis (counted from zero). Bending fatigue strength of steel hardened from 880oC subject to tempering temperatures and its average oxygen contents is shown in Fig. 6. The correlation coefficients for each curve are high, above 0.97. The directional coefficients of the curves are similar, therefore, for a specific oxygen content in the steel, the tensile strength decreases with increasing the tempering temperature. The lines are arranged sequentially from the lowest oxygen content in the steel (viewed from the bottom) to the highest (line at the top). Thus, with the increase of oxygen content in high purity steel, the fatigue strength increases. However, this increase is not significant. It should be emphasized that the considerations are carried out for a small proportion of oxygen in steel. This can be explained by the effect of inhibiting stress concentration in steel with the use of oxygen.

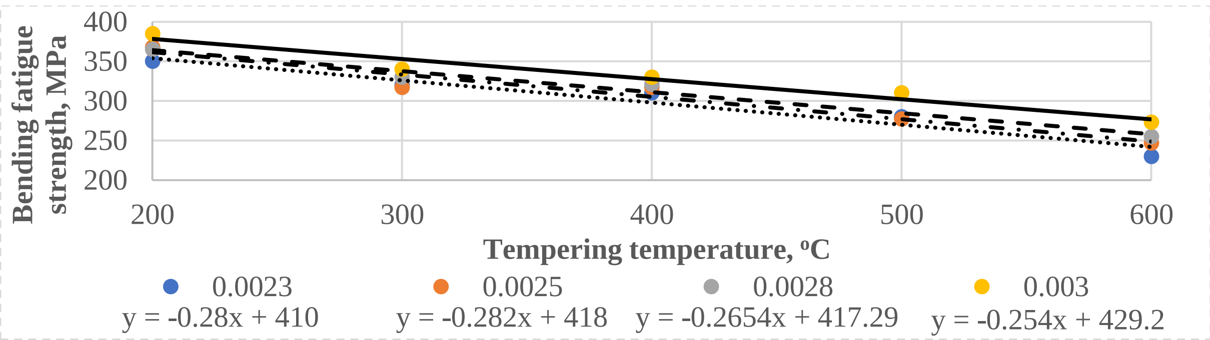

Fig. 6. **Bending fatigue strength of steel hardened from 880 ºC subject to tempering temperatures and its average oxygen contents**

Conclusions

1. The oxygen of impurities influence on the bending fatigue strength of low carbon steel depends on its tempered temperature. It decreased from 368 to 252 MPa when the tempering temperature changed from 200 to 600 ºC.
2. As the oxygen content increased from 0.0023% to 0.003%, the average flexural strength (for all tempering temperatures) increased from 298 to 328 MPa.

Author contributions

Conceptualization, T.L.; methodology, T.L.; validation T.L.; formal analysis T.L.j J.P.; writing and editing, J.P. and T.L.; All authors have read and agreed to the published version of the manuscript.

References

[1] Gulyakov V. S., Vusikhis A. S. & Kudinov D. Z., Nonmetallic Oxide Inclusions and Oxygen in the Vacuum Jet Refining of Steel. Steel in Translation 42/11, 2012, pp. 781–783.

[2] Srivastava A., Ponson L., Osovski S., Bouchaud E., Tvergaard V., Needleman A., Effect of inclusion density on ductile fracture toughness and roughness. Journal of the Mechanics and Physics of Solids 63, 2014, pp. 62–79.

[3] Lipiński T., Wach A., Effect of the impurities on the bending fatigue strength of structural steel. 14th International Scientific Conference Engineering for Rural Development Proceedings vol. 14, Jelgava, 20.-22.05.2015, pp. 784-789.

[4] Spriestersbach D., Grad P., Kerscher E., Influence of different non-metallic inclusion types on the crack initiation in high-strength steels in the VHCF regime, International Journal of Fatigue 64, 2014, pp. 114-120.

[5] Evans M.H. and all, Confirming subsurface initiation at non-metallic inclusions as one mechanism for white etching crack (WEC) formation. Tribology International 75, 2014, pp. 87–97.

[6] Lipiński T., Effect of the Spacing Between Submicroscopic Oxide Impurities on the Fatigue Strength of Structural Steel. Archives of Metallurgy and Materials Vol. 60/3b, 2015, pp. 2385-2390,

[7] Selejdak J., Blikharskyy Y., Khmil R., Blikharskyy Z., Calculation of Reinforced Concrete Columns Strengthened by CFRP. In: Blikharskyy, Z., Koszelnik, P., Mesaros, P. (eds) Proceedings of CEE 2019. CEE 2019. Lecture Notes in Civil Engineering , vol 47. Springer, 2020, pp. 400-410.

[8] Campbell G.S., Lahey R., A survey of serious aircraft accidents involving fatigue fracture. International Journal of Fatigue 6, 1984, pp. 25–30.

[9] Suresh S., Fatigue of Materials. Cambridge University Press: Cambridge, UK, 1998.

[10] Lankford J., Initiation and early growth of fatigue cracks in high strenght steel, Engineering Fracture Mechanics 9, 1977, pp. 617-624.

[11] Tkachenko, R., Duriagina, Z., Lemishka, I., Izonin, I., Trostianchyn, A., Development of machine learning method of titanium alloy properties identification in additive technologies. Eastern-European Journal of Enterprise Technologies 3(12-93), 2018, pp. 23–31.

[12] Murakami Y., Kodama S., Konuma S., Quantitative evaluation of effects of non-metallic inclusions on fatigue strength of high strength steels, I: basic fatigue mechanism and fatigue fracture stress and the size and location of non-metallic inclusions, International Journal of Fatigue 11/5, 1989, pp. 291–298.

[13] Lipiński T., Wach A., Detyna E., Influence of Large Non-Metallic Inclusions on Bending Fatigue Strength Hardened and Tempered Steels. Advances in Materials Science 15/3 (45), 2015, pp. 33-40.

[14] Murakami Y., Nomoto T., Ueda T., Factors influencing the mechanism of super long fatigue failure in steels. Fatigue & Fracture of Engineering Materials & Structures 22, 1999, pp.581–590.

[15] Ivanytskyj Y.L., Lenkovskiy T.M., Molkov Y.V., Kulyk V.V., Duriagina Z.A., Influence of 65G steel microstructure on crack faces friction factor under mode fatigue fracture. Archives of Materials Science and Engineering 82(2), 2016, pp. 49-56.

[16] Zrnik, J., Pippan, R., Scheriau, S., Kraus, L., Fujda, M., Microstructure and mechanical properties of UFG medium carbon steel processed by HPT at increased temperature. Journal of Material Science 45, 2010, pp. 4822-4826.

[17] Lipiński T., Wach A., Influence of inclusions on bending fatigue strength coefficient the medium carbon steel melted in an electric furnace. Production Engineering Archives Vol. 26/3, 2020, pp. 88-91.

[18] Roiko A., Hänninen H., Vuorikari H., Anisotropic distribution of non-metallic inclusions in forged steel roll and its influence on fatigue limit, International J. of Fatigue 41, 2012, pp.158-167.

[19] Palček, P., Oravcová, M., Chalupová, M., Uhríčik, M., The Usage of SEM for Fatigue Properties Evaluation of Austenitic Stainless Steel AISI 316L. Manufacturing Technology 16(5), 2016, pp. 1110-1115.

[20] Chan K. S., Roles of microstructure in fatigue crack initiation, International Journal of Fatigue 32, 2010, pp. 1428–1447.

[21] Kim, H., Choi, M., Chung, C., Shin, D., Fatigue crack growth behavior in ultrafine grained low carbon steel. KSME International Journal 16, 2002, pp. 1246-1252.

[22] Studený Z., Dobrocky D., Pokorny Z., Importance of Diffusion Process on the Fatigue Life of Steel Manufacturing Technology 17(1), 2017, pp. 94-99.
[23] Hua L., Deng S., Han X., Huang S., Effect of material defects on crack initiation under rolling contact fatigue in a bearing ring, Tribology International 66, 2013, pp. 315–323.
[24] He X, Wang M., Hu C., Xu L. Study of the relationship among total oxygen, inclusions and fatigue properties of gear steel. Materials Science & Engineering A 827 (2021) 141999.
[25] Kerscher, E., Lang, K.-H., Vöhringer, O., Löhe, D., Increasing the fatigue limit of a bearing steel by dynamic strain ageing. International Journal of Fatigue 30, 2008, pp. 1838-1842.
[26] Nishijima S., Kanazawa K., Stepwise S–N curve and fish-eye failure in gigacycle fatigue. Fatigue Fatigue & Fracture of Engineering Materials & Structures 22, 1999, pp. 601–607.
[27] Sangid M.D., The physics of fatigue crack initiation, International Journal of Fatigue. 57, 2013, pp. 58–72.
[28] Park J. S., Park J. H., Effect of Slag Composition on the Concentration of Al2O3 in the Inclusions in Si-Mn-killed Steel. Metallurgical and Materials Transactions B 45B, 2014, pp. 953-960.
[29] Murakami Y., Kodama S., Konuma S., Quantitative evaluation of effects of non-metallic inclusions on fatigue strenght of high strength steels. International Journal of Fatigue 11, 1989, pp. 291-298.
[30] Lipiński T., Wach A., Influence of Outside Furnace Treatment on Purity Medium Carbon Steel. 23rd International Conference on Metallurgy and Materials Metal 2014 Brno TANGER Ltd., Ostrava. Conference proceedings 2014, pp. 738-743.
[31] Gulyakov V. S., Vusikhis A. S., Kudinov D. Z., Nonmetallic Oxide Inclusions and Oxygen in the Vacuum_Jet Refining of Steel. Steel in Translation 42/11, 2012, pp. 781–783.
[32] Murakami Y., Metal fatigue. Effects of small defects and inclusions. Elsevier 2002.
[33] Závodská D., Guagliano M., Bokůvka O., Trško L., Effect of Shot Peening on the Fatigue Properties of 40NiCrMo7 steel. Manufacturing Technology 16(1), 2016, pp. 299 – 304.
[34] Kłysz S., Selected problems of fatigue of materials and constructions elements. Technical Science 8, 2005, pp. 141-164.
[35] Mitchell M.R., Fundamentals of Modern Fatigue Analysis for Design, Fatigue and Fracture 19, ASM Handbook, ASM International, 1996.
[36] Srivastava A., Ponson L., Osovski S., Bouchaud E., Tvergaard V., Needleman A., Effect of inclusion density on ductile fracture toughness and roughness. Journal of the Mechanics and Physics of Solids 63, 2014, pp. 62–79.
[37] Halford G. L., Low cycle thermal fatigue. NASA 1986.
[38] Lipiński T., Wach A., Size of Non-Metalic Inclusions in High-Grade Medium Carbon Steel. Archives of Foundry Engineering. Vol. 14/4, 2014, pp. 55-60.
[39] Blikharskyy Z., Bruzda K., Selejdak J., Effectivenes of Strengthening Loaded RC Beams with FRCM System. Archives of Civil Engineering 64/3, 2018, pp. 3-13.
[40] Foletti S., Beretta S., Tarantino M. G., Multiaxial fatigue criteria versus experiments for small crack under rolling contact fatigue, Int. Journal of Fatigue 58, 2014, pp. 181–182.
[41] Dudek A., Wlodarczyk R., Structure and properties of bioceramics layers used for implant coatings. Solid State Phenomena 165, 2010, pp. 31-36.
[42] Szczotok A., Pietraszek J., Radek N., Metallographic Study and Repeatability Analysis of γ' Phase Precipitates in Cored, Thin-Walled Castings Made from IN713C Superalloy. Archives of Metallurgy and Materials 62/2, 2017, pp. 595-601.
[43] Antosz K., Pacana A., Comparative analysis of the implementation of the SMED method on selected production stands. Tehnicki Vjesnik 25, 2018, pp. 276-282.
[44] Pacana A., Ulewicz R., Analysis of causes and effects of implementation of the quality management system compliant with iso 9001. Polish Journal of Management Studies 21/1, 2020, pp. 283-296.
[45] Baryshnikova N., Kiriliuk O., Klimecka-Tatar D., Enterprises' strategies transformation in the real sector of the economy in the context of the COVID-19 pandemic. Production Engineering Archives 27/1, 2021, pp. 8-15.
[46] Pietraszek J., Gądek-Moszczak A., Radek N., The estimation of accuracy for the neural network approximation in the case of sintered metal properties. Studies in Computational Intelligence 513, 2014, pp. 125-134.
[47] Pietraszek J., Radek N., Goroshko A.V., Challenges for the DOE methodology related to the introduction of Industry 4.0. Production Engineering Archives 26(4), 2020, 190-194.