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Enhancing the surface hardness and roughness of engine blades using the shot peening process

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Abstract: The effects of shot peening on the mechanical properties of steel 1070 were studied to enhance the material's properties and surface characteristics. In this study, pressure and exposure time were the main parameters governing surface hardness and surface roughness. The optimal time duration and pressure were determined after several experimental trials. Changes in hardness and surface roughness were monitored as the pressure of the shot and the exposure time were varied. Furthermore, the microstructure was evaluated by scanning electron microscopy (SEM) and the images were enhanced by image processing techniques to evaluate the surface changes. Pareto charts were constructed to estimate the effects of pressure and time on both surface hardness and surface roughness. The novelty of this study is the concentration on engine blades which are frequently used in aircrafts to determine the optimal time–pressure combination for shot peening to achieve suitable mechanical and surface properties. The results show that shot peening pressure (up to 482.6 kPa for 7 min) has positive effect on enhancing the surface and mechanical properties for steel 1070 blades; however, an increase in either pressure or time above that level adversely affected both surface hardness and surface roughness.

Keywords: shot peening; roughness; hardness; engine blades; scanning electron microscopy

1. Introduction

Various materials with enhanced properties compared with those of mono-materials and composite materials are now available from various sources. Although composites have several advantages, including being light weight and low cost and exhibiting suitable environmental aspects and electrical functional properties [1–3], steel is still required in various functional mechanical applications. The shot-peening process is assumed to be a cold-working process in which aspherical beads (produced mainly from metal or glass) are shot at high velocity to dent the surface of the metal to (1) improve certain mechanical properties such as the strength of the metal and its ability to resist corrosion and (2) increase the surface hardness and eventually extend the lifespan of mechanical parts by creating a residual compressive stressed layer on the surface of the part [4]. The literature showed that treatment of this layer plays a vital role in enhancing the mechanical properties of its surface.

Many studies have been carried out with regard to changing the mechanical properties of materials by varying different parameters. Jia and Ji [5] have experimentally studied the effects of shot-peening parameters on a hot-forging die. The microhardness of the die surface was improved after shot peening. They verified their experimental results by putting five sets of modules into service. The working life of the strengthened dies was longer than that for untreated dies. The original mold was capable of producing approximately 8000 pieces, whereas the shot-peened die produced more than 9000 pieces. Umemoto *et al*. [6] evaluated the formation of a nanocrystalline structure on steel samples using two methods: particle-impact and air-blast shot peening. nanocrystalline layers with high hardness and with characteristics similar to those produced by ball milling and ball-drop deformation were successfully generated by these methods. The authors concluded that, to produce nanocrys-

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talline-structured layers, rapid strain and low temperatures are promising conditions. Zhan *et al*. [7] used X-ray stress analysis to study the surface yield strength of S30432 steel after different shot-peening treatments. The results revealed that the proof stress of the peened surface increased to approximately 830 MPa after conventional treatment and to 940 MPa after dual shot peening; by comparison, bulk S30432 had a yield strength of 268 MPa. Chang *et al*. [8] investigated the effect of peening on both the thermal and mechanical properties of H13 tool steel by impacting the surface of the steel at high speed, which resulted in a surface more highly resistant to both thermal fatigue and stress corrosion cracking. The treated tool steel had its life extended by a factor of two to three.

Unal and Varol [9] investigated the effect of severe shot peening on the microstructure and mechanical properties of AISI 1017 mild steel. The surface characteristics were studied using different optical microscopy techniques such as scanning electron microscopy (SEM) and high-resolution transmission electron microscopy. The results showed that this approach was an excellent method to achieve an ultra-fine-grained surface layer along with superior mechanical properties. Llaneza and Belzunce [10] tested six different steel grades obtained from AISI 4340 by subjecting them to shot peening with different shot sizes and air pressures. They then subjected the peened specimens to fatigue tests to study their mechanical properties. They concluded that maximizing the lifespan of this industrial steel was a challenging task because many parameters will affect its lifespan, as described in their research. Unal [11] studied the shot-peening parameters that affect the height of the arch of a strip, its surface hardness, and its surface roughness. ANOVA analysis was used to build a model regarding process inputs (pressure, shot size, and peening time) and process outputs (surface hardness and surface roughness) to optimize the peening conditions and then verify the model using the tests. Even for severe shot peening such as that carried out by Llaneza and Belzunce [10], the results showed an improvement in the fatigue life, hardness, and even the surface microstructure of the steel.

The main aim of the present work was to experimentally study the effect of shot-peening parameters (i.e., shot pressure and time duration) on some mechanical and surface properties, such as the hardness, roughness, and microstructure, of carbon steel 1070. This grade of steel is used in many applications, including aircraft engine blades, and in the general agricultural field. In our case, numerous samples from the same material as that used for aircraft engine blades were peened after a certain number of flying hours to enhance their mechanical and microstructural properties so that the service life of the engines could be increased. A literature survey revealed that this kind of steel in conjunction with our studied parameters (i.e., the peening time and pressure) and their effects on hardness and roughness has not been previously studied. Therefore, the novelty of this work was to concentrate on engine blades frequently used in aircraft and to determine the optimal time–pressure combination for shot peening to achieve suitable mechanical and surface properties according to our application.

2. Experimental

Aircraft engine blades are made from different materials or alloys to withstand high temperatures and pressures. Alloys such as nickel-based superalloys or iron-based stainless steels are suitable for this purpose. In our case, carbon steel 1070 was used to represent the materials that engine blades are made from (Fig. 1). The strip had the following specifications. Carbon steel 1070 specimens with rectangular shape (length: 76 mm, width: 19 mm, and thickness: 1.32 mm). The reported chemical composition of the material was 98.3wt%–98.8wt% Fe, 0.65wt%–0.75wt% C, 0.6wt%–0.9wt% Mn, 0wt%–0.05wt% S, 0wt%–0.04wt% P. Mechanical properties reported by the manufacturer are given in Table 1, as published on the website (MakeIt-From.com) [12]. Shot peening was carried out using a Pangborn peening machine available at Jordan Airmotive.

Fig. 1. Examined specimens.

Table 1. Mechanical properties of intact specimens

Modulus of elasticity / GPa	Yield strength / MPa	Ultimate strength / MPa
210	410–570	640–760

Constant parameters in the experiment were a table speed of 5.5 r/min, a distance from the nozzle of 100 mm, and conditioned carbon steel wire (cut wire shot, CCW-14) as the shot material.

The variable conditions investigated included three different pressures (206.8, 482.6, and 689.5 kPa) and three different exposure times (4, 7, and 10 min); these specific values were predetermined on the basis of the literature and after some trials using longer exposure times were conducted [9,11]. For each set of conditions, three specimens were tested for hardness using the Vickers microhardness test and for roughness using a TR100 surface roughness tester, resulting in a total of 27 tests. The results were averaged and tabulated for each of the three specimens, as shown in Table 2. The microstructure of each specimen was subsequently observed by SEM (model JEOL JSM-6510LV). The accelerating voltages available were 0.5 to 30 kV, and the magnification range was from 5× to 300,000×. All images were taken at 2000× magnification using an 18-kV accelerating voltage; the edges were then detected using an image processing technique to make comparisons clearer.

3. Results and Discussion

3.1. Quantitative results

The results for the 27 specimens are illustrated in Table 2, where (Reference) refers to the not peened specimen. To effectively study the data, we designed an experimental matrix (Table 2) consisting of the inputs (pressure and peening duration) and the corresponding averaged outputs (hardness, roughness, and arch height). The results obtained after the values for the three specimens for each set of parameters were averaged are included in Table 2. In these samples, the No. 5, No. 14, No. 23 and the (Reference) samples were evaluated by SEM.

Table 2. Design of experimental matrix showing the inputs and corresponding averaged outputs

Samples#	Inputs		Outputs		
	Pressure / kPa	Peening duration / min	Average hardness, HV	Average roughness / μm	Average arch height / mm
(Reference)	0	0	800	0.11	0.0056
1, 2, 3	206.8	4	810	0.56	0.0668
4, 5, 6	206.8	7	983	0.64	0.0693
7, 8, 9	206.8	10	982	0.82	0.0838
10, 11, 12	482.6	4	994	1.37	0.1234
13, 14, 15	482.6	7	1100	1.27	0.1455
16, 17, 18	482.6	10	1104	1.43	0.1321
19, 20, 21	689.5	4	1030	1.5	0.1600
22, 23, 24	689.5	7	1050	1.65	0.170
25, 26, 27	689.5	10	1070	1.78	0.165

Surface roughness is an important factor that strongly affects fatigue strength and heat transfer. Fig. 2 shows the effect of increasing pressure on surface roughness for the three different exposure times. The roughness increased when the pressure increased at all of the exposure times; this behavior is related to the damage occurring on the specimen surface [11,13]. Thus, on the basis of the required standard of roughness, we can select the optimum treatment pressure according to standard uses for aircraft engine blades.

Fig. 3 shows the effect of increasing pressure on specimen hardness for the three different exposure times. Initially, the hardness increased as the pressure was increased to 482.6 kPa. At this stage, a relatively thin compressive layer had formed, and this hardened layer improved the mechanical properties of the specimens [14]. This effect is explained as follows: when displacements occur, the atoms barely below the surface try to resist the displacements; thus, compressive stresses are generated to restore the surface to its original state. These stresses harden the surface and resist crack formation and propagation [15]. Afterwards, the hardness begins to decrease because of the excessive peening, which leads to weakening of the surface material, which in turn activates self-annealing of the surface [13,16].

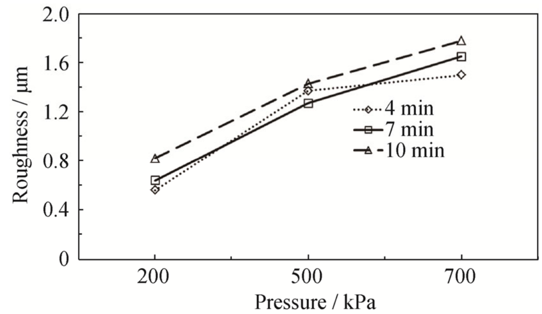

Fig. 2. Effect of pressure and time on surface roughness.

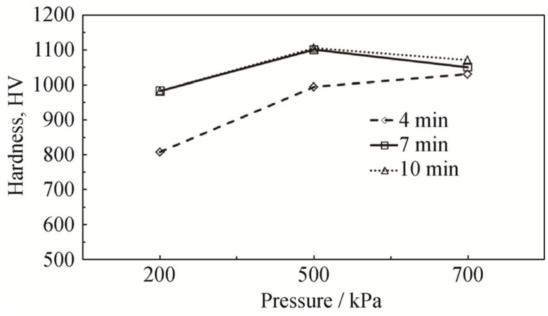

Fig. 3. Effect of pressure and time on surface hardness.

Fig. 4 shows the effect of increasing pressure on specimen arch height for the three different exposure times. The pressure is the dominant factor and time plays only a minor role in increasing the arch height [17].

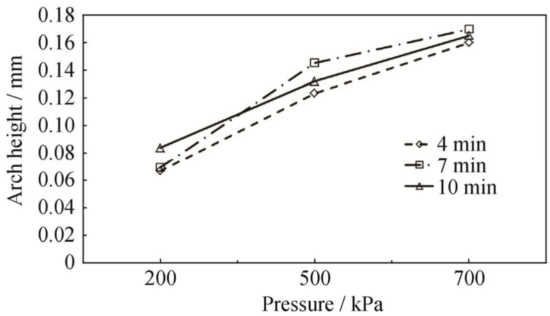

Fig. 4. Effect of pressure and time on arch height.

To study the interaction effect of the different parameters, the MINITAB software was used to produce Pareto charts for each studied output. Figs. 5–7 show the effect of the investigated parameters on the specimen hardness, roughness, and arch height, respectively. Pressure has the main effect on all three parameters studied [16], followed by the effect of exposure time. Interaction between them has no effect, as evident from the Pareto charts.

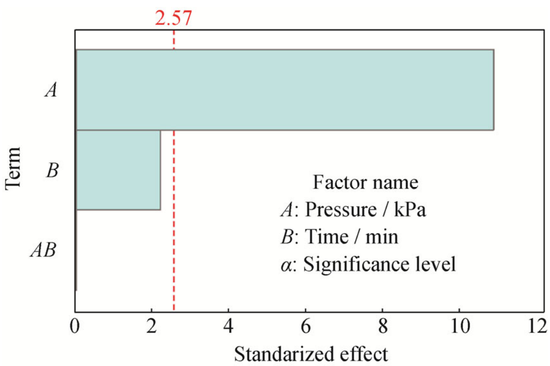

Fig. 5. Pareto chart of the effects of correlations and interrelations of the inspected factors on surface roughness (response is roughness avg. (μm), $\alpha = 0.05$).

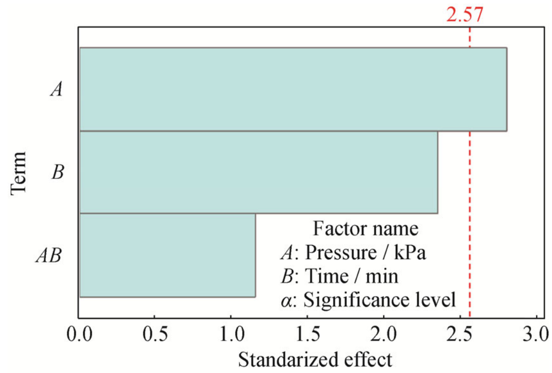

Fig. 6. Pareto chart of the effects of correlations and interrelations of the inspected factors on surface hardness (response is hardness avg. (HV), $\alpha = 0.05$).

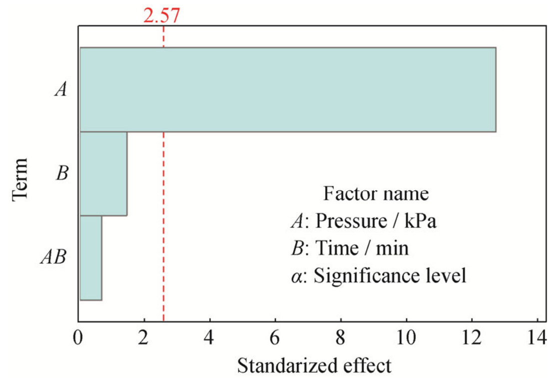

Fig. 7. Pareto chart of the effects of correlations and interrelations of the inspected factors on arch height (response is arch height avg. (mm), $\alpha = 0.05$).

3.2. Qualitative evaluation

During the peening process, substantial changes in the surface microstructure were observed. SEM images for specimens at different stages are shown in Fig. 8. Images on the left side (Figs. 8(a), 8(c), 8(e) and 8(g) show the original micrographs captured using electron microscopy. Images on the right side (Figs. 8(b), 8(d), 8(f) and 8(h)) show modifications to binary images in which the background is converted to white and the percentage of microcracks and area of defects relative to the area of the whole image are calculated using an image processing technique.

Fig. 8(a) shows the intact specimen and Fig. 8(b) shows the image after conversion into a binary image as a trial to measure the area of defects relative to the area of the whole image. The red groups indicate the dislocation clusters and microcracks. The percent area of defects is 13.98% relative to the whole area, which can be explained by the formation of defects during the manufacturing processes of the workpieces [18–20].

The SEM images (Figs. 8(c) and 8(d)) that correspond to specimen No. 5 (206.8 kPa, 7 min) show some reduction in the percentage of defects, which decreased to 11.38% relative to the whole image area. Appreciable enhancement of the microstructure was observed when the pressure was increased to 482.6 kPa for the same time (7 min), as shown in Figs. 8(e) and 8(f) (percent area of defects, 5.6%). With an increase of the pressure to 689.5 kPa for the same duration (Figs. 8(g) and 8(h)), the surface improvement stopped and the surface deteriorated (percent area of defects, 23.1%); these results agree with the quantitative data shown in Table 2.

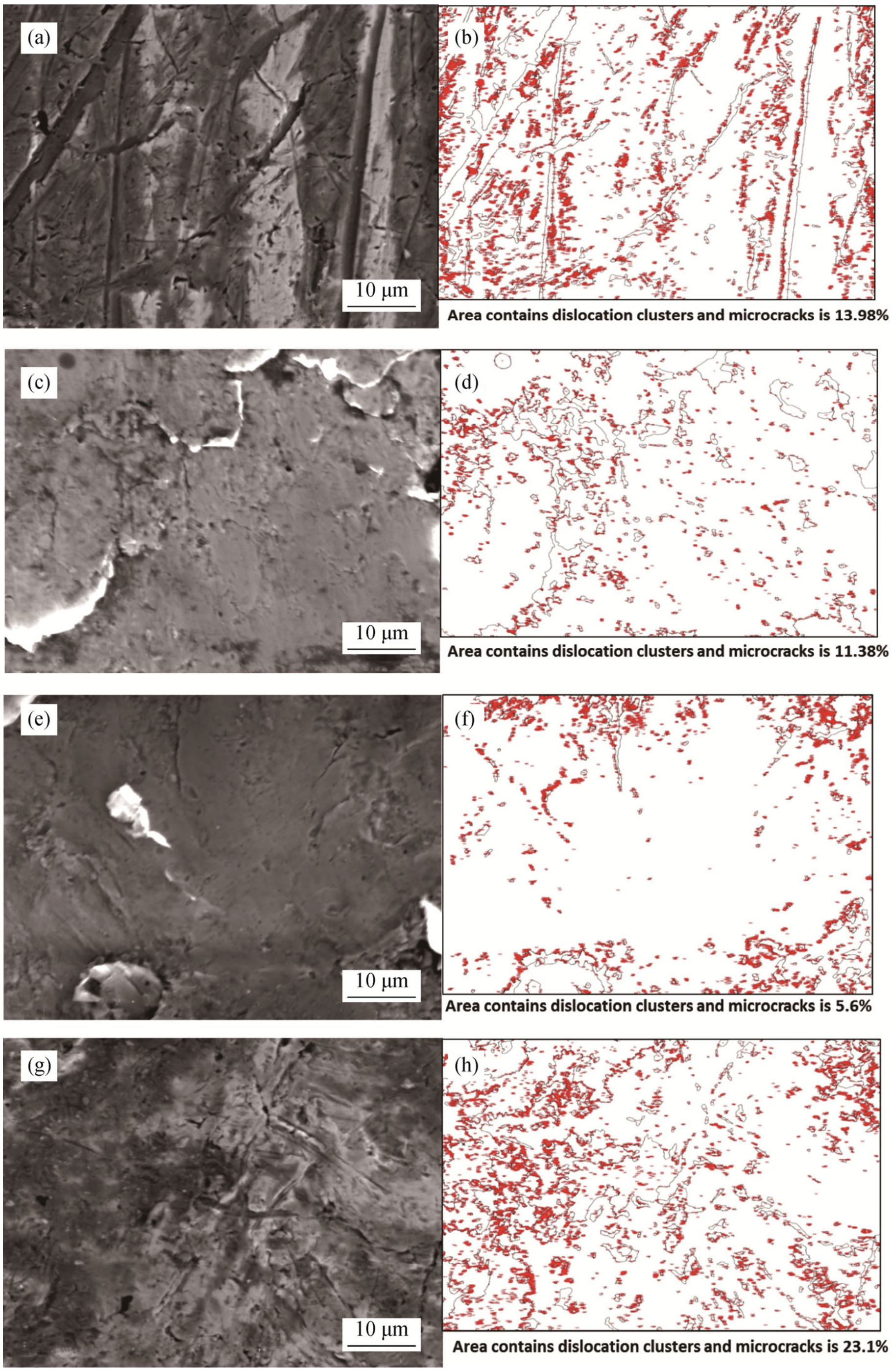

Fig. 8. Microstructure for different stages of peening: (a–b) specimen as received ((Reference) sample); (c-d) 206.8 kPa for 7 min peening (No. 5 sample); (e–f) 482.6 kPa for 7 min peening (No. 14 sample); (g–h) 689.6 kPa for 7 min peening after the third stage (No. 23 sample).

4. Conclusions

This paper focused on enhancing the mechanical and surface properties of 1070 steel by using the shot-peening process. From the set of experiments on the peened specimens, including measurements of hardness, roughness, and arch height and analysis of SEM micrographs, we drew the following conclusions.

(1) The main factor that affects the studied parameters is the pressure of the shot particles; exposure time has a less pronounced effect.

(2) In analysis of the SEM micrographs for different pressures and durations, the effect of pressure was again observed to play the major role in enhancing the hardness and surface properties.

(3) The improvement continues until a certain pressure is reached, above which increasing pressure has a negative effect due to strain hardening of the peened surface.

(4) On the basis of this experimental study, we can select the best time–pressure combination to obtain adequate hardness with minimum roughness according to application requirements.

Acknowledgement

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References

[1] F.M. AL-Oqla, A. A. Omar, and F. Osama, Evaluating sustainable energy harvesting systems for human implantable sensors, *Int. J. Electron.*, 105(2018), No. 3, p. 504.

[2] F.M. AL-Oqla, Investigating the mechanical performance deterioration of Mediterranean cellulosic cypress and pine/polyethylene composites, *Cellulose*, 24(2017), No. 6, p. 2523.

[3] F.M. AL-Oqla and M.S. Salit, *Materials Selection for Natural Fiber Composites*, 1st ed., Woodhead Publishing, Cambridge, 2017.

[4] X.F. Li, J. Zhang, M.M. Ma, and X.L. Song, Effect of shot peening on hydrogen embrittlement of high strength steel, *Int. J. Miner. Metall. Mater.*, 23(2016), No. 6, p. 667.

[5] Z. Jia and J.J. Ji, Influence analysis of shot peening on hot forging die, *Int. J. Adv. Manuf. Technol.*, 90(2016). No. 5-8, p. 1779.

[6] M. Umemoto, Y. Todaka, and K. Tsuchiya, Formation of nanocrystalline structure in steels by air blast shot peening, *Mater. Trans*., 44(2003), No. 7, p. 1488.

[7] K. Zhan, C.H. Jiang, and V. Ji, Surface mechanical properties of S30432 austenitic steel after shot peening, *Appl. Surf. Sci.*, 258(2012), No. 24, p. 9559.

[8] S.H. Chang, T.P. Tang, and F.C. Tai, Enhancement of thermal cracking and mechanical properties of H13 tool steel by shot peening treatment, *Surf. Eng.*, 27(2013), No. 8, p. 581.

[9] O. Unal and R. Varol, Almen intensity effect on microstructure and mechanical properties of low carbon steel subjected to severe shot peening, *App. Surf. Sci.*, 290(2014), p. 40.

[10] V. Llaneza and F.J. Belzunce, Optimal shot peening treatments to maximize the fatigue life of quenched and tempered steels, *J. Mater. Eng. Perfom.*, 24(2015), No. 7, p. 2806.

[11] O. Unal, Optimization of shot peening parameters by response surface methodology, *Surf. Coat. Technol*., 305(2016), p. 99.

[12] Makeitfrom, *SAE-AISI 1070 (C70, 1.1520, G10700) Carbon Steel*, [2018-05-05], https://www.makeitfrom.com/material-properties/SAE-AISI-1070-C70-1.1520-G10700-Carbon-Steel.

[13] C. Xu, G.M. Sheng, H.D. Wang, J.Y. Jiao, and X.J. Yuan, Effect of high energy shot peening on the microstructure and mechanical properties of Mg/Ti joints, *J. Alloys Compd.*, 695(2017), p. 1383.

[14] J.E. Rodriguez-Sanchez, A. Rodriguez-Castellanos, and F. Perez-Guerrero, Shot peening effect on fatigue crack repaired weldments, *Adv. Mater. Sci. Eng.*, 2017(2017), art. No. 3720403.

[15] D. Kirk, Residual stresses in shot peened components, *The Shot Peener*, 18(2004), p. 26.

[16] L.S. Hetram, L. Singh, and H. Om, Shot peening effects on material properties: Review, *Int. J. Innovative Res. Sci. Technol.*, 1(2015), No. 12, p. 480.

[17] P. Sanjurjoa, C. Rodrígueza, I.F. Parientea, F.J. Belzuncea, and A.F. Canteli, The influence of shot peening on the fatigue behaviour of duplex stainless steels, *Procedia Eng*., 2(2010), No. 1, p. 1539.

[18] H.Y. Miao, D. Demers, S. Larose, C. Perron, and M. Lévesque, Experimental study of shot peening and stress peen forming, *J. Mater. Process. Technol.*, 210(2010), No. 15, p. 2089.

[19] M.A. Omari and I. Sevostianov, Estimation of changes in the mechanical properties of stainless steel subjected to fatigue loading via electrical resistance monitoring, *Int. J. Eng. Sci.*, 65(2013), p. 40.

[20] D. Hul and D.J. Bacon, *Introduction to Dislocations*, 4th ed., Butterworth-Heinemann, Oxford, 2011.