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Vibratory Shot Peening of Elements Cut with Abrasive Water Jet

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ABSTRACT
The paper presents the effect of technological parameters of vibratory shot peening on the roughness and microhardness of the surface layer of shot peened objects. Moreover, the surface topography results from vibratory shot peening was analyzed. In the experiment, samples made of 1.4301 stainless steel were used, which were cut by abrasive water jet (AWJ). The geometrical structure of the surface after vibratory shot peening was changed. The surface roughness was obtained in the range of Rsk = -0.600 ÷ -1.115 and Sa = 3.01÷6.53 μm, The value of microhardness ΔHV, near to the surface, is from 36 HV0.05 to 100 HV0.05. The changes in microhardness reach on the depth g_h = 100 μm. An analysis of variance ANOVA for the investigated dependent variables was performed. The Tukey's test was used to checked the influence of the independent variable on the dependent variable. The aim to obtain favorable properties of the surface layer of elements after abrasive water jet cutting, it is recommended to use a vibratory shot peening time of approx. 6 minutes and balls of diameter *d* = 6 mm.

Keywords: vibratory shot peening, abrasive water jet cutting, stainless steel, surface roughness, microhardness, statistical analysis.

INTRODUCTION

Abrasive water jet (AWJ) cutting is one of the unconventional methods of material cutting. The benefits in contrary to other popular cutting techniques are the lack of the heat-affected zone, no heating up of the object, existence of minimum cutting force on the work materials and high cutting precision. The advantages of AWJ also include the production of a better surface integrity than the laser cutting process and higher material removal rate than the Wire EDM [1].

In AWJ, material removal takes place through two predominant modes as a result of microcutting such as cutting and deformation/ploughing deformation erosive wear mechanism [1]. Cutting deformation happens through sharp-edged, angular particles, whereas, ploughing deformation is significant for spherical abrasive particle. In erosion process, material removal occurs through crack propagation and chipping as a result of contact stresses caused during the impact of abrasive particles [1, 2].

The AWJ machined surface is divided into three regions with different quality. Zone 1 is a damage region near the top of the cutting kerf. It is happens due to the expansion of the jet prior to hitting the material and the difference in jet energy. Zone 2 is called the smooth region and zone 3 is named the damaged region, distinguished by large waviness profile. The quality of smooth region is dependent of the abrasive particle size, while the condition of the third region depends on jet kinetic energy [1].

Due to the wide use the stainless steel in many industries and more challenges to the machining this materials, the AWJ machining very often used for cutting anyintricate profile and drill holes in extensive range in this materials [3]. The use of AWJ technology for cutting stainless steel causes high roughness of surface after cutting. Based on the results presented in [4, 5], the authors concluded that growth the cutting speed cause an increase in surface roughness. It is one of the factors that significantly influence on the surface roughness [4]. On the surface of the cut specimens, two areas of different roughness are visible [4, 6], that the width of which changes with the cutting speed. The surface roughness depends also on process parameters: abrasive material type, shot size and morphology, pressure, standoff distance, and abrasive mass flow and many more [5]. It has been observed that an increase in AWJ cutting process parametres, except grain size, causes an increase in surface roughness [5].

The positron annihilation method was used to determine the crystal lattice defects in stainless steel 304 samples, that were processed by three cutting techniques. It was shown that AWJ cutting creates lattice defects, edge dislocations and vacancies, which are at short distance from the cut surface.The total depth of the subsurface zones is extendend up 40 μm from the cut surface, while for milling it is 150 μm [7]. Defect detection can also be localized by recurrence and entropy methods, as proposed in [8]. Research on polymer composites, which are more and more widely studied [9], with this method, allows to determine the location of the defect and its size. The AWJ cutting process does not cause microstructural changes [10]. There is only a slight increase the hardness close to the surface, there is the so-called the "crush" effect [11].

The occurring imperfections and irregularities make it difficult to use the part in the next production stage. The application of the paint or galvanic coatings is difficult. Currently ball burnishing [12] and centrifugal shot peening [13] are successfully used as finishing of items made by blasting and erosive treatment. Work is also underway to use of brushing, which generates low machining forces [14], to improve the quality of the surface after AWJ cutting [15]. Therefore, it seems reasonable to take research aimed at the use of vibratory shot peening to changed the geometric structure of the surface and improve the physical properties of the surface layer of stainless steel components.

The characteristic feature of shot peening is that the shot elements freely impact on the workpiece surface. At the same time, the shot peened surfaces undergoes sepecific changes in roughness, strain state or microstructure.

During vibratory shot peening (VSP) the balls impact is caused by the vibrations of the working chamber, in which the workpieces (usually clamped) and loose peening elements are located. Vibratory shot peening can be applied to objects with complex shapes, both small and large, as well as rotating and non-rotating. This creates great possibilities of using this technology as a finishing of objects with complex shapes and made with various methods.

As a result of shot peening (SP), the properties of the surface layer are changed, which leads to changes in the functional properties of objects after this treatment. After vibratory shot peening of materials used in the aviation industry (Ti6Al4V titanium alloy and E-16NiCrMo13 steel), it is possible to obtain the surface roughness parameter Ra at the level of $Ra = 0.3 \div 0.4$ μm [16]. Comparing the surface roughness parameters obtained by vibratory shot peening (VSP) to the shot peening (SP), it was observed that after VSP, the roughness parameters decreased, while after SP they increased compared to the values before [17].The beneficial effect of shot peening is hardening surface layer and generation of compressive residual stresses [18–21]. The values of residual stresses created by vibratory shot peening are comparable to those obtained after conventional shot peening, however their depth occurrence is much greater [16, 17].

Moreover, the type of shot peening media (CrNi steel shot, nutshell granules and ceramic beads) affects the wear and corrosive behaviour of additive manufactured stainless steel 17-4PH [22]. Walczak and Szala reports that shot peening caused microstructure refinement and except for the nutshell shot-peened specimens, induced both martensite (α) formation and retained austenite (γ) reduction. Morover the peening process increasing the ratio of surface hardnening.

The occurrence of compressive residual stresses in the surface layer increase the fatigue life of elements after vibratory shot peening [23–25]. The growth the microhardness of the surface layer obtained after vibratory shot peening allows to improvement of the tribological properties of ASIS 1020 steel elements processed with this method [26]. The method of surface preparation, vibratory shot peening can be successfully used influence on the adhesive properties of surfaces, which translates into the strength of adhesive joints made of Ti6Al4V titanium alloy and other materials [27–29]. Vibratory shot peening has been successfully used as a combined treatment with laser shock peening [30]. A combination of these two technologies caused a rearrangement of the high-density dislocations. This resulted the increase fatigue life and formation of more homogeneous surface nanostructure [30].

The aim of this work is to determine parameters of vibratory shot peening that allow obtaining low surface roughness and microhardness increase of cut surface.

METHODOLOGY OF RESEARCH

In the research, the samples with dimensions of 4×8×100 mm were cut using the commercial WaterJet system produced by BMTC WJ4040-1Z-D1, from the austenitic stainless steel plate, grade 1.4301 (according to PN EN 10088 1:2007). This material is widely used in food industry equipment, tanks and pipelines. 1.4301 steel is characterized by excellent plastic properties, good magnetic properties and weldability [31]. The overview of research methodology is presented in Figure 1.

The first stage of the experiment was the AWJ cutting. Standard parameters were used for cutting (cutting speed: 327 mm/min, water pressure: 360 MPa, type of abrasive: Garnet #80, abrasive efficiency: 500 g/min and distance between the nozzle and the object: 2 mm). Then vibratory shot peening tests were performed.

In order to carried out the vibratory shot peening, the samples were attached to the bottom of the working chamber (Fig. 2a), than covered with steel balls (made from 100Cr6 steel) (the so-called "charge") (Fig. 2a), which stated 1/3 of the working chamber height. The vibratory shot peening was carried out on a mechanical-kinematic vibrator (Fig. 2c), using the following processing conditions:

- vibratory amplitude a = 5 mm,
- frequency of vibration v = 2100 1/min
- shot peening balls diameter d = 3; 6; 9 mm
- shot peening time t = 1; 6; 15 min.

The Hommel-Etamic T800 RC 120-140 device was used to measurements the topography (parameters 3D) and surface roughness (parameters 2D) before and after vibratory shot peening. Measurements of surface roughness were made at the distance equal to 1/3 of the thickness of the workpiece, from the upper cut edge – the so-called "entrance" zone and at the distance equal to 1/3 from the lower edge – the so-called "exit" zone. It was made according to EN ISO 9013: 2017 (Thermal cutting - Classification of thermal cuts - Geometrical product specification and quality tolerances). The choice of two areas for measuring surface roughness resulted from occurrence of characteristic zone of different quality. The area of the scanned surface was 4.8×4.8 mm.

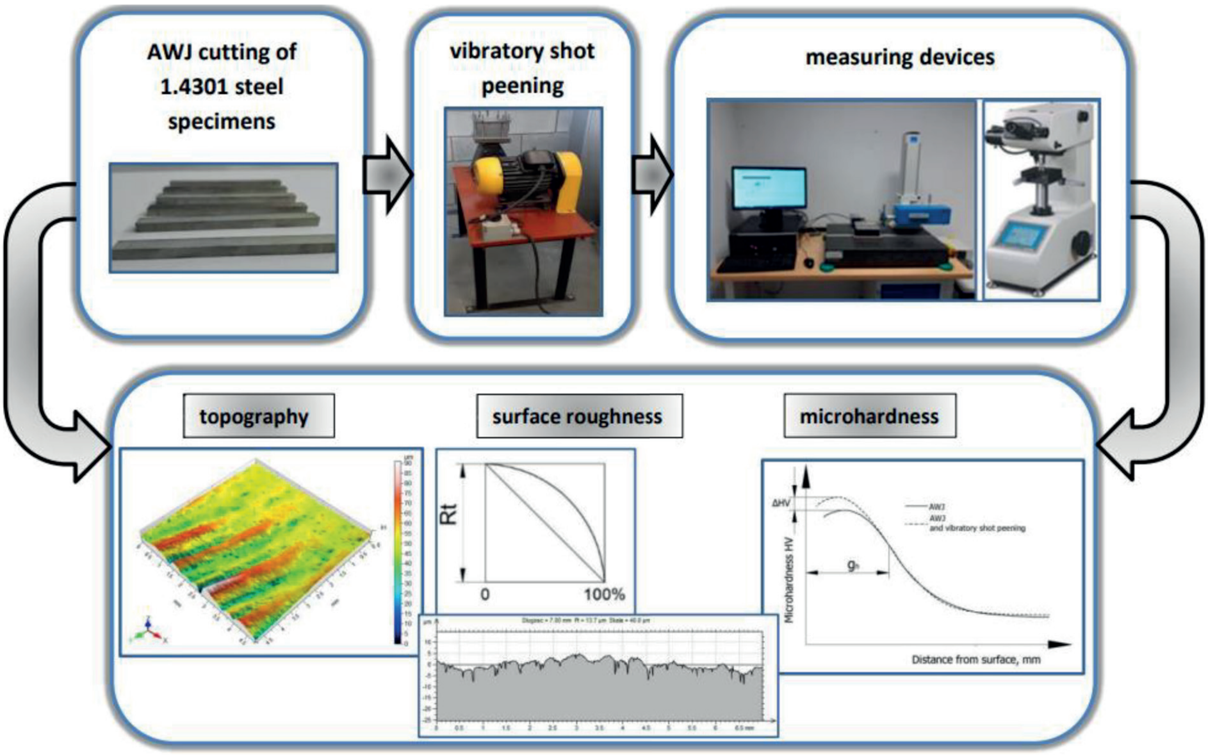


Fig. 1. The research methodology applied in current study, description in the text

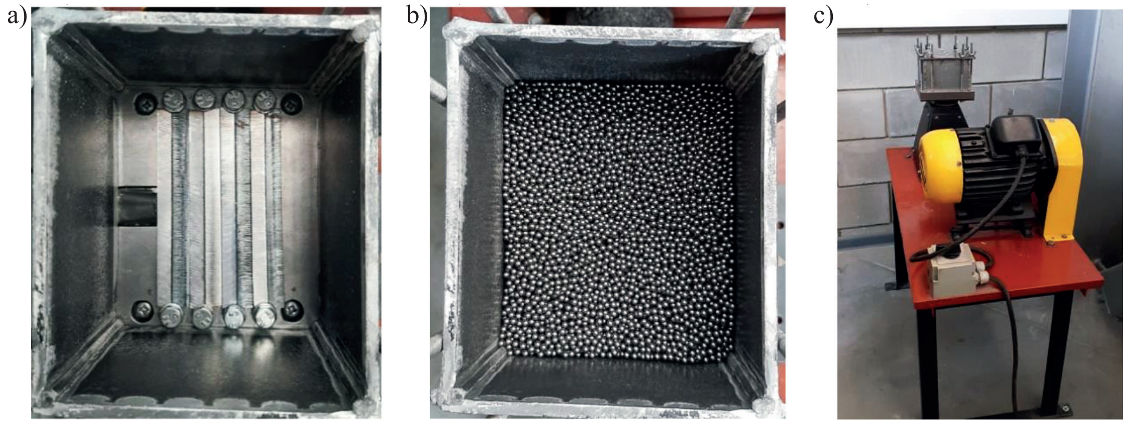


Fig. 2. Stand for vibratory shot peening: (a) working chamber with samples, (b) working chamber with charge, (c) mechanical-kinematic vibrator

The analyzed parameters of 3D surface roughness (according the PN-EN ISO 25178-2:2012) and 2D (according the PN-EN ISO 4287:1999) were:
Sa – arithmetical mean height of the surface,
Sz – maximum height of the surface,
Sp – maximum peak height of the surface,
Sv – maximum pit height of the surface,
Ssk – skewness,
Rt – total height of the roughness profile,
Rsk – profile asymmetry coefficient (skewness).

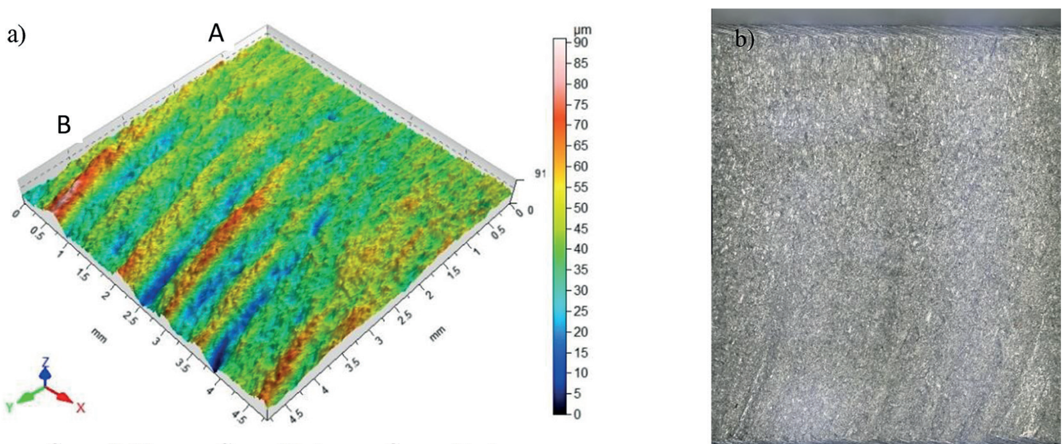
The Vickers method was used to measurement the microhardness. The diagonal sections after standard treatment was applied. The measurements were made in accordance with the EN-ISO 6507-1:2018 standard. An LM 700at microhardness tester was used with an indenter load of 50 gf (HV 0.05).

For the tested variables in the work (roughness parameters, microhardness an increase ΔHV 0.05 and the thickness of the hardened layer g_h), an analysis of the significance of the influence of the parameters of vibratory shot peening on the obtained results was carried out. The Statistica software version 13 was used to perform the analysis of variance (ANOVA). Before the ANOVA analysis, the normality of data distribution was examined. The Shapiro-Wilk test was used. The Levene test was used to estimate the homogeneity of variance. The significance level α = 0.05 was taken in all the analysis. The analysis of the effect of the independent variables (shot peening balls diameter – *d* and shot peening time – *t*) was verified by means of post-hoc tests (Tukey test).

RESULTS AND DISCUSSION

Surface topography

Figure 3 shows the cut surface 3D topography, areal roughness parameters and exemplary cut



Sa = 7.83 µm; Sz = 83.1 µm; Sp = 41.4 µm;
Sv = 41.7 µm; Ssk = 0.227

Fig. 3. Topography and roughness of cut surface (a), cut surface with visible drag lines (b)

surface obtained after AWJ cutting. On the surface characteristic stripes are visible, created as a result of cutting. In the “entrance” zone (A) is an even pattern of micro-inequalities, while in the “exit” zone (B) is a visible deviation of stripes from the direction of movement of abrasive water jet. The curved shape of the stripes in the lower area indicate that the material “slip away” from the kerf.

After vibratory shot peening is visible a flattening of the micro-inequalities formed after AWJ cutting on the surface. During the impact of the balls in the processed surface, the friction phenomenon is intensified, which cause intensive shearing of the micro-inequalities, which reduces their height. It means the decrease in the value of the *Sp* and growth the absolute value of the *Ssk* parameter [12, 13]. As the vibratory shot peening time increases, the differences between the summits and pits of micro-inequalities is decreased (Fig. 4). The use balls with a larger diameter cause the increase of the impact energy, there is a greater degree of micro-inequality deformation, which allows for a more than 2-fold reduction of the Sa and Sz parameters (Fig. 4) (*d* = 9 mm, *t* = 6 min). The absolute value of the skewness parameter *Ssk* also increases, which suggests that the material was concentrated around the peaks of the profile. The surface with a negative skweness coefficient should be considered as a surface characterized by a greater ability to transfer contact loads and lower tribological wear of the surface in the presence of a lubricant [32].

Surface roughness

Figure 5 shows the influence of the input factors on the roughness parameter Rt. As expected, an increase in the vibratory peening time causes a decrease total height of the roughness profile (Fig. 5a).

The decrease in the value of the analyzed roughness parameter should be explained by the increase the impact density (the number of impact per unit area), which occurs with the increase of the vibratory shot peening time. The growth the multiple impacts balls on the peened surface causes the multiple deformation of the same micro-inequalities. The obtained value of the parameter Rt for “entrance” zone and “exit” zone are much lower than the values after AWJ cutting. The horizontal line in Figure 5 (“orange” and “blue”) shows the parameter Rt before vibratory

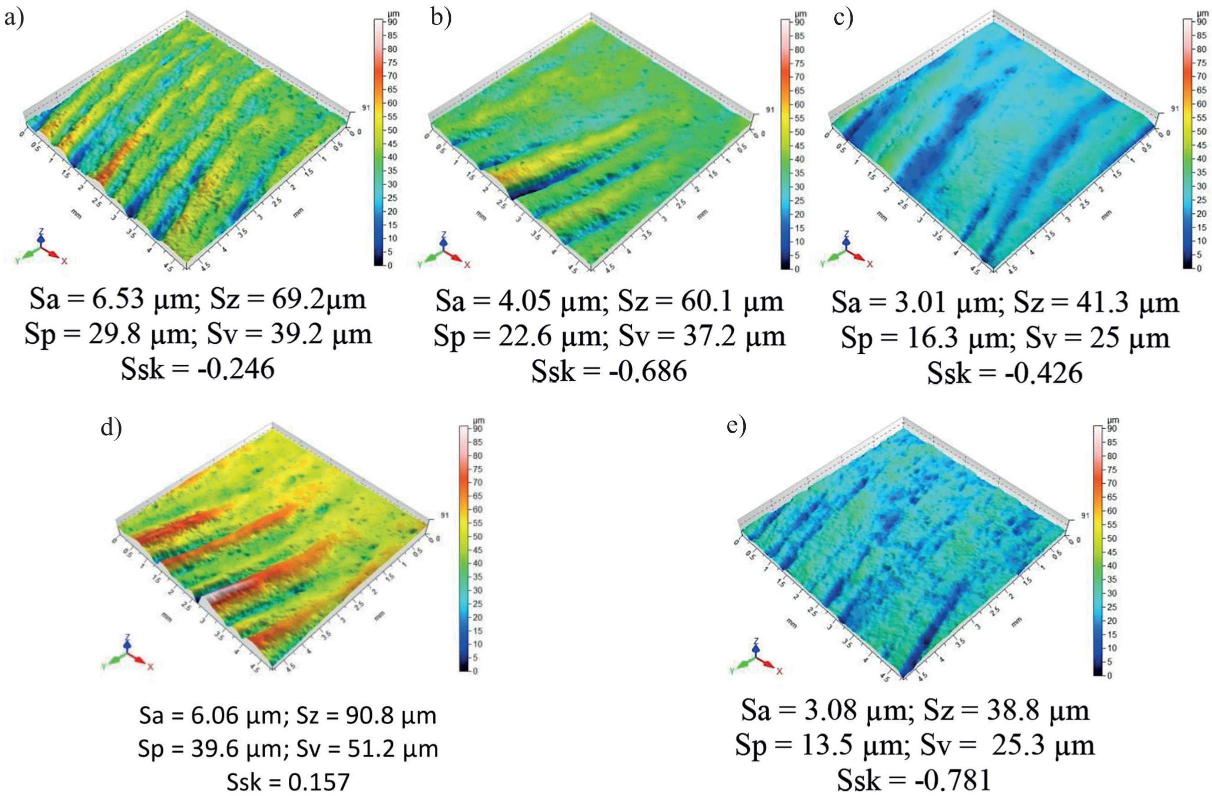


Fig. 4. The influence of vibratory shot peening parameters on the surface topography and 3D roughness parameters for specimens after AWJ cutting: a) *t* = 1 min, *d* = 6 mm; b) *t* = 6 min, *d* = 6 mm; c) *t* = 15 min, *d* = 6 mm; d) *d* = 3 mm, *t* = 6 min; e) *d* = 9 mm, *t* = 6 min

shot peening. For the "entrance" zone state of "saturation" occurs for vibratory shot peening time greater than t = 6 min. There are no statistically significant differences (confirmed by the ANOVA variance test and then by the post-hoc test: Tukey's test) (Table 1). However in the "exit" zone, it can be noticed that the change of time from t = 1 min to t = 6 min does not significantly impact on the Rt parameter. The obtained changes in the parameter Rt, as a function of vibratory shot peening time are consistent with own previous research carried out on samples made of 30HGSA steel [33].

The use of a ball greater than d = 6 mm causes that the contact of the balls with the sample surface is large. At the same time, an increase in the ball diameter causes the growth the impact energy, which causes intense plastic and elastic deformations of the striated structure, which results in decrease in the Rt parameter in the "exit" zone. Similar changes in the height parameter of the roughness profile as a function of the ball diameter were obtained during the impulse shot peening of the Inconel 718 nickel alloy [34]. In the case of the "entrance" zone, the change in the diameter of the balls from 3 to 6 mm causes a slight decrease in the analyzed parameter. The performed statistical analysis confirms that, the change in the diameter of the vibratory shot peening balls in the tested range, has a statistically significant influence on the obtained values of the Rt parameter (Table 1).

In the vibratory shot peening time range t = 1÷6 min for the "entrance" zone and for t = 6÷15 min for the "exit" zone, slight changes in the Rsk parameter value are visible (Fig. 6a).There are

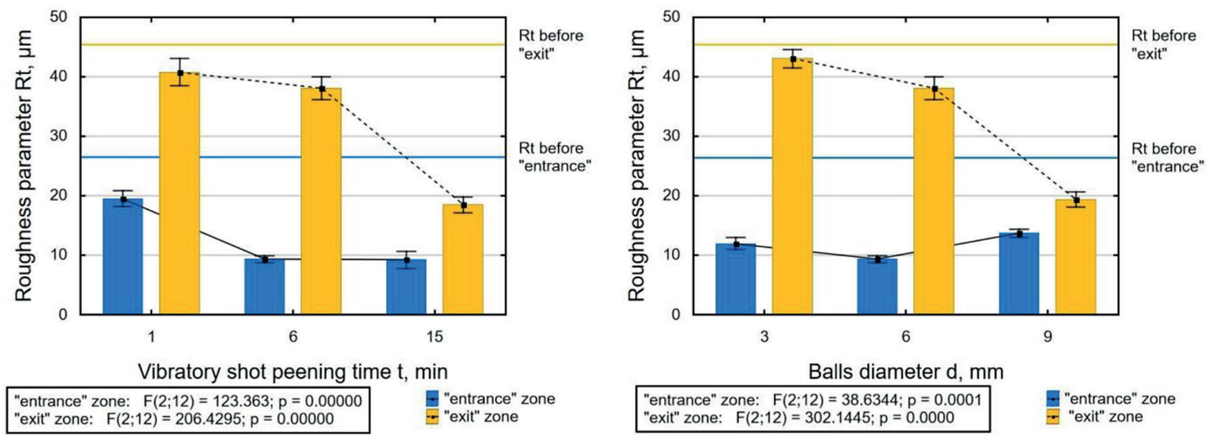


Fig. 5. Effect vibratory shot peening time (d = 6 mm) (a) and balls diameter (t = 6 min) (b) on the roughness parameter *Rt*

Table 1. Comparative analysis of the differences between the *Rt* roughness parameter after the vibratory shot peening. The red color mean no statistically significant differences

Roughness parameter Rt							
"Entrance" zone							
Vibratory shot peening time t [min]				Balls diameter d [mm]			
	1	6	15		3	6	9
1		0.00019	0.00019	3		0.00069	0.01208
6	0.00019		0.98329	6	0.00069		0.00019
15	0.00019	0.98329		9	0.01208	0.00019	
"Exit" zone							
Vibratory shot peening time t [min]				Balls diameter d [mm]			
	1	6	15		3	6	9
1		0.10546	0.00019	3		0.00122	0.00019
6	0.10546		0.00019	6	0.00122		0.00019
15	0.00019	0.00019		9	0.00019	0.00019	

a) b)

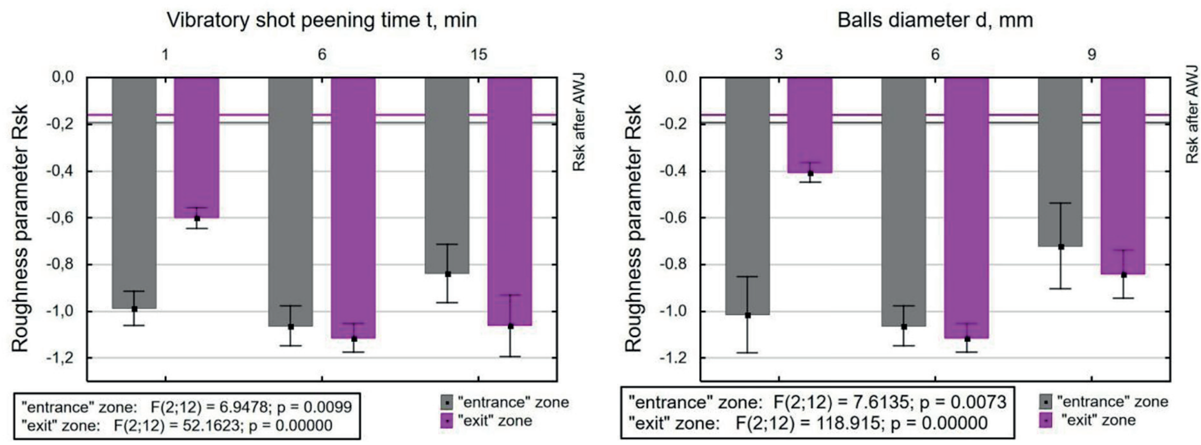


Fig. 6. Effect vibratory shot peening time (d = 6 mm) (a) and balls diameter (t = 6 min) (b) on the roughness parameter *Rsk*

no statistically significant differences, which was confirmed by the post-hoc test (Table 2). The obtained absolute values of the skewness coefficient Rsk are much greater in relation to the value after AWJ cutting (Fig. 6a).

In the figure 6b influence the balls diameter on the roughness parameter Rsk was presented. The use of balls greater than d = 3 mm causes a significant deformation of the micro-inequalities after AWJ cutting in the "exit" zone, a flattening of the roughness profile take place and the absolute value of the Rsk coefficient increases. The changes occurring should be explained by the increase of the impact energy, together with the use of balls with a larger diameter. In the case of the "entrance" zone, there are no statistically significant changes for ball shot peening with the use ball d = 3 mm and d = 6 mm (Table 2).

Microhardness

As a result of shot peening, an increase the number of dislocations takes place. The dislocations propagate and were halted when they encountered other dislocations. The occurring phenomenon of the blockage the dislocations contributed to the increase the microhardness of the surface layer (Fig. 7) [23, 34]. The increase in microhardness may also be caused by phase changes [22]. The increase the microhardnes is also after AWJ cutting at a depth of about 10 µm, which is consistent with the results described in [11]. The increase in microhardness close to the surface, obtained as a result of vibratory shot peening, ranged maximum of approx. 100 HV and the hardened layer thickness is up to 100 µm.

Table 2. Comparative analysis of the differences between the roughness parameter *Rsk* after the vibratory shot peening. The red color mean no statistically significant differences

Roughness parameter Rsk							
"Entrance" zone							
Vibratory shot peening time *t* [min]				Balls diameter *d* [mm]			
	1	6	15		3	6	9
1		0.67379	0.05594	3		0.86577	0.02360
6	0.67379		0.01212	6	0.86577		0.00945
15	0.05594	0.01212		9	0.02360	0.00945	
"Exit" zone							
Vibratory shot peening time *t* [min]				Balls diameter *d* [mm]			
	1	6	15		3	6	9
1		0.00019	0.00019	3		0.00019	0.00019
6	0.00019		0.61491	6	0.00019		0.00036
15	0.00019	0.61491		9	0.00019	0.00036	

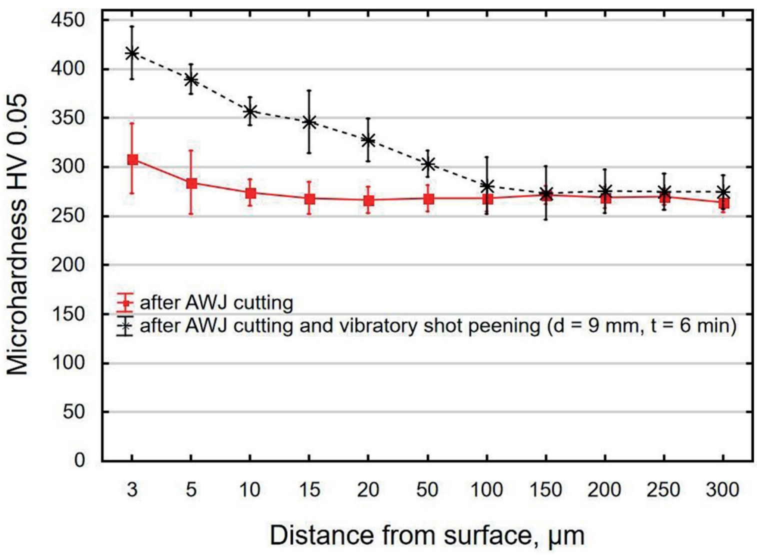


Fig. 7. Distribution of the microhardness of 1.4301 steel surface layer after AWJ cutting and AWJ cutting and vibratory shot peening (*d* =9 mm, *t* = 6 min)

Figure 8 shows the influence of technological parameters on the increase in microhardness (ΔHV) and the thickness of the hardened layer (g_h). Increasing the vibratory shot peening time *t* causes an increase in the values of ΔHV and g_h. It is caused by the increase of the impact density (multiple hitting the balls in the same place), which increases with the shot peening time (Fig. 8a). The changes in the shot peening time, with in the range of the experiment carried out, have a statistically significant influence on the ΔHV and g_h (Table 3). An increase *d* causes extension of the indentation surface area, resulting from the impact. This carry on to reduction of the concentration of energy transferred to the workpiece, which in consequence causes a decrease in the value of the relative increase in microhardness ΔHV (Fig. 8b). Similar dependencies were obtained in my earlier work on semi random and regular shot peening of EN-AW 7075 aluminium alloy [35]. The change the diameter from d = 6 mm to d = 9 mm does not cause statistically significant variation in the value of ΔHV (Table 3). Analyzing the graph shown in Figure 8b, it should be noted that the graph of g_h versus *d* is flatter compared to Figure 8a. This means that, as the diameter of the balls increases, the value of the microhardness near at the surface decreases, but the depth of hardening of the surface layer increases. The obtained maximum increase the microhardness and the depth of the hardened layer after vibratory shot peening of samples made of 1.4301 steel

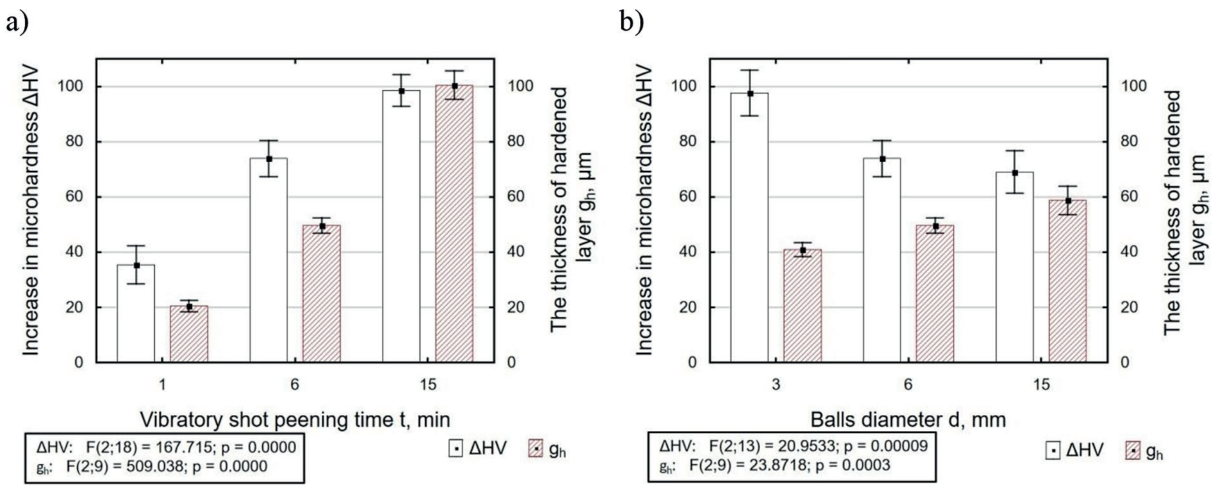


Fig. 8. Effect vibratory shot peening time (*d* = 6 mm) (a) and balls diameter (*t* = 6 min) (b) on the increase in microhardness ΔHV and the thickness of the hardened layer g_h

Table 3. Comparative analysis of the differences between the increase in microhardness ΔHV and the thickness of the hardened layer g_h after the vibratory shot peening. The red color mean no statistically significant differences

ΔHV							
Vibratory shot peening time *t* [min]				Balls diameter *d* [mm]			
	1	6	15		3	6	9
1		0.000149	0.000149	3		0.000460	0.000346
6	0.000149		0.000150	6	0.000460		0.543963
15	0.000149	0.000150		9	0.000346	0.543963	
g_h							
Vibratory shot peening time *t* [min]				Balls diameter *d* [mm]			
	1	6	15		3	6	9
1		0.000184	0.000183	3		0.020103	0.000355
6	0.000184		0.000183	6	0.020103		0.016131
15	0.000183	0.000183		9	0.000355	0.016131	

after AWJ cutting are lower than the results described in [25]. It is probably related to the type of shot peened material and the condition of the geometric structure before processing.

CONCLUSIONS

Based on the research carried out on the effect of parameters of vibratory shot peening on selected properties of the surface layer of samples made of stainless steel grade 1.4301 after AWJ cutting, the following conclusions can be drawn:

- after vibratory shot peening, it is possible to obtain the surface roughness (Rt parameter), 2.5 times smaller than after AWJ cutting,
- after vibratory shot peening, the absolute value of the skewness coefficient Rsk increases, which means that this surface will be characterized by less abrasive wear in the use of the lubricant,
- the performed vibratory shot peening reduces the differences in the values of the analyzed parameters of surface roughness between the "entrance" zone and the "exit" zone, it is especially visible when using balls with the diameter of $d = 9$ mm and time $t = 6$ min,
- after vibratory shot peening of samples after AWJ, the surface topography is changed, the stripes formed on the machined surface are flattened,
- in the surface layer of the samples there is an increase in microhardness, the ΔHV value of which is from 38 HV0.05 to 100 HV0.05, and the thickness of the hardened layer is from 19 μm to 100 μm, the maximum value of microhardness is 455 HV 0.05 for ($d = 6$ mm, $t = 15$ min),
- the analysis of variance ANOVA and Tukey's test showed that in most cases there are statistically significant differences, when changing the independent variables,
- taking into account the obtained properties of the surface layer, as a result of vibratory shot peening and statistical analysis, it can be concluded that the shot peening time $t = 6$ min and the diameter of the balls $d = 6$ mm can be considered as optimal parameters in this case.

Aknowledgments

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