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# The Effect of Vibratory Shot Peening on the Geometric Structure of the Surface of Elements Machined by Laser and Abrasive Water Jet Cutting

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## ABSTRACT

Elements machined by laser and abrasive water jet cutting sometimes require the use of a finishing treatment. One of the finishing methods for machined elements is vibratory shot peening (VSP). This paper presents the influence of VSP technological conditions on the surface topography and surface roughness (parameters Ra and Rsk) of aluminium alloy AW-7075 samples. Experiments were carried out according to the following plan: first, vibratory shot peening (VSP) was conducted using balls with a diameter d = 3 mm, 6 mm and 9 mm. Then, the surfaces of the samples after VSP (treated with 6 mm diameter balls) were subjected to re-vibratory shot peening (RVSP). As a result of vibratory shot peening, the Ra parameter of the specimens after laser cutting decreased by 71% to 91%, while for the AWJ-treated elements it decreased by 56% to 85%. The additional operation decreased the Ra parameter in the entry zone by 4% to 6% for the samples after laser cutting and by 5% to 7% for the samples after AWJ, when compared to the Ra value after single vibratory shot peening conducted using balls with d=6 mm. After VSP and RVSP, the surface topography of the samples changed. Vibratory shot peening led to the creation of "striations" on the shot-peened surface that could not be completely removed. The re-vibratory shot peening operation (for specific conditions) had a positive effect on the geometric structure of the surface of the elements after cutting. Both VSP and RVSP caused reduction in the analysed 3D surface roughness parameters.

**Keywords:** surface roughness, surface topography, vibratory shot peening, finishing treatment, aluminium alloy AW-7075.

## INTRODUCTION

Construction materials can be cut and machined by mechanical methods (cutting on guillotines, presses, shears) and by erosive methods (laser beam cutting, plasma beam cutting, abrasive water jet cutting, oxygen cutting).

Laser cutting and abrasive water jet cutting are effectively used as the first technological operation in the manufacturing of many machine components. The first successful tests on using a laser beam to divide engineering materials were conducted in the 1970s, while abrasive water jet cutting was tested in the early 1980s. Owing to their many advantages and a wide range of applications, both methods for dividing engineering materials are considered to be the basic techniques of advanced construction technology. Currently, these technologies are efficiently used in the aviation, automotive, machine-building industries for the manufacture of basic components [1, 2].

Laser cutting (LC) and abrasive water jet cutting (AWJ) are complementary in many aspects. Laser cutting allows for the use of higher cutting speeds, while the unit cost of this cutting technique is lower than that in abrasive water jet cutting [2]. The advantages of the AWJ cutting over laser cutting include: the possibility of cutting materials with greater thickness; no thermal deformation;

no material hardening; the possibility of cutting multilayer materials and materials covered with rust; no burr formation [1, 3]. Among others, the advantages of AWJ cutting include the ability to remove material at a higher speed than that applied in Wire EDM [4].

In spite of the above, basic elements made with these technologies often require finishing. The methods for finishing machine components is burnishing (B) and shot peening (SP). In this technology, plastic deformation induced by a contact of the burnishing or shot peening element with the surface of the workpiece is used during machining.

After shot peening the properties of the surface layer change. The effect of shot peening leads to reduced surface roughness [5]. After SP compressive residual stresses occur in the surface layer of the workpiece [5÷7], which is one of the factors contributing to improved fatigue life of machined components [8, 9]. Microstructure and microhardness, corrosion and wear performance also change after shot peening [10]; in addition, defects can be formed on the surface layer [11÷13], which can be determined via annihilation techniques [14] as well as recurrence and entropy methods [15]. The type of treatment and the method of surface preparation also influence on surface free energy [16, 17]. Studies [18, 19] showed that shot peening could refine the grain size of material. Grain refinement was found to lead to a significant improvement in material strength compared to the material matrix [19].

The effects of SP depend on many factors such as shot peening coverage, peening intensity, peening velocity, shot size [20, 21], and shot material type [10]. Numerical studies showed that an increase in the speed shot peening speed caused a significant increase in the refining layer thickness as well as in the compressive residual stress layer and deep maximum compressive residual stress [20]. However, the use of a ball with a larger diameter in the dry shot peening of AISI 316L implant materials, led to a reduction in their surface roughness [21]. The obtained values of surface roughness parameters were higher than after the pre-treatment. In the shot peening of AISI 316L stainless steel, passivated and porosity-free layers were produced, which allowed the corrosion resistance to increase. A study [20] found that the corrosion resistance increased with decreasing the size of a steel ball diameter.

The current trend is to combine different techniques (shot peening + precise grinding) or operations (severe shot peening (SSP) + re-shot peening (RSP)), which is an effective way of ensuring favourable properties of the surface layer of workpieces. A study [22] investigated the impact of SP, SSP and RSP and precise grinding on selected properties of AISI 1050 railway axle steel. The results showed that RSP (conducted at lower intensities) and precise grinding improved the surface roughness of the AISI 1050 steel elements. The use of a two-stage operation (SSP+RSP) had a positive effect on the depth of residual stresses and their values. It was also found that re-shot peening had a greater effect on low-cycle fatigue performance, while severe shot peening affected high-cycle fatigue performance. Maleki E et al. [19] found that re-shot peening had a positive effect on microhardness, grain refinement, residual stresses, and surface roughness reduction after severe shot peening (SSP). The application of RSP after conventional shot peening (CSP) or SSP in the machining of AISI 304 steel was proved to be an effective way of reducing surface roughness. The use of re-shot peening (RSP) was found to lead to the formation of mechanical twins and strain-induced martensite [23].

One variation of shot peening is vibratory shot peening (VSP). In vibratory shot peening, the workpiece is fixed in the working chamber with shot peening balls. The shot peening elements exert impact on the workpiece due to vibrations of the working chamber. In vibratory shot peening the entire surface is machined at the same time. Vibratory shot peening can be used as a finishing treatment for rotating and non-rotating elements with complex shapes, as well as for smaller and larger elements. An advantage of vibratory shot peening over shot peening is that this technique makes it possible to obtain lower surface roughness (after VSP the Ra value decreased by 25% and that of Rt by 16%; while after SP Ra increased by 656% and Rt by 772% compared to their values for as-machined samples) [24]. In the vibratory shot peening of Ti-6Al-4V and E-16NiCrMo13, one can obtain a surface roughness of Ra = 0.3 ÷ 0.4 μm [25]. The tribological properties of the ASIS 10120 grade steel are improved after vibratory shot peening [26]. Residual stresses induced after VSP are located at greater depths than those after SP, but their value is comparable to that obtained after shot peening [24].

In order to reduce the negative effects of laser cutting, the following methods are currently used: coating the surface of the cut material with a special chemical substance reducing the formation of metal overhang [27], mechanical grinding [28], diamond smoothing [29], ball burnishing [30], and centrifugal shot peening [31]. A previous study has confirmed the validity of using vibratory shot peening as a finishing treatment for stainless steel 1.4301 after AWJ cutting [32], while Matuszak efficiently used brushing to rebuild the geometric structure of the surface of aluminium alloy EN-AW 7075 [33].

Based on the literature review and previous studies, it can be concluded that a combination of burnishing and shot peening is an effective way of ensuring favourable properties of the surface layer of elements after laser cutting and AWJ cutting. The use of RSP afterwards also yields positive results in the machining of engineering materials. Previous studies on the vibratory shot peening of stainless steel 1.4301 elements after AWJ confirmed this observation. However, it seems that the type of cutting technology used (laser or water-abrasive jet) can have a significant impact on the effects obtained after vibratory shot peening, which is the reason why this study was undertaken. The aim of the study is to evaluate the impact of technological parameters of VSP on the geometric structure of the surface of aluminium alloy AW-7075 elements after laser cutting and abrasive water jet cutting. The literature review demonstrates that the stereometric properties of the surface layer after laser and AWJ cutting vary, which can have a significant impact on after vibratory shot peening results.

## RESEARCH METHODOLOGY

The tests were performed on aluminium alloy AW-7075 samples which were cut to the size of 4 x 8 x 100 mm using a laser (one batch) and a water-abrasive jet (the other batch). A TruLaser 3030 laser cutter from Trumpf was used for laser cutting. The following cutting parameters were used: speed: 2.2 m/min; power: 3000 W; pulse frequency: 20 000 Hz; gas pressure: 15 MPa; gas type: nitrogen. Typical parameters were used for AWJ cutting. They were as follows: speed: 316 mm/min; abrasive capacity: 500 g/min; water pressure: 360 MPa; abrasive type: Garnet #80; nozzle-to-work distance: 2 mm. The cutting tests were performed on a Waterjet Streamcut 4121 cutter from Kimla.

The next stage of the experiment was vibratory shot peening. It was conducted on a vibrator in which the working chamber was located. The workpieces made of AW-7075 aluminium alloy after laser cutting and abrasive water jet cutting were fixed to the bottom of the working chamber. After that, the chamber was filled with steel balls (the so-called "batch"). Balls with a d = 3 mm, 6 mm and 9 mm were used. The charge was 1/3 of the height of the working chamber. The chamber was set in motion using a vibration frequency of ν = 2100 1/min and an amplitude of a = 5 mm. The vibratory shot peening time was maintained constant at t = 6 min. Multiple VSP was used in the tests, and it involved carrying out one vibratory shot peening operation after another. Figure 1 shows the experimental methodology and the stand used to evaluate the geometric structure of the surface of the samples. Table 1 lists a set of technological parameters used in the tests.

A Hommel-Etamic T8000RC 120–140 device from Hommel-Werke was used to measure surface topography and roughness. According to the EN ISO 9013:2017 standard, for objects thicker than 2 mm, surface roughness measurements should be taken at a distance of 1/3 of the sample thickness from the upper edge, i.e. "entrance zone". Control measurements were made at a distance of 1/3 from the lower edge of the cut. The map with the location of the surface

**Table 1.** Vibratory shot peening conditions

| No. | | Type of technology | d [mm] | t [min] |
|---|---|---|---|---|
| 1 | | Single vibratory shot peening | 3 | 6 |
| 2 | | | 6 | |
| 3 | | | 9 | |
| 4 | a | Re-vibratory shot peening | 6 | |
| | b | | 3 | |
| 5 | a | | 6 | |
| | b | | 9 | |

**Note:** a – first step, b – second step.

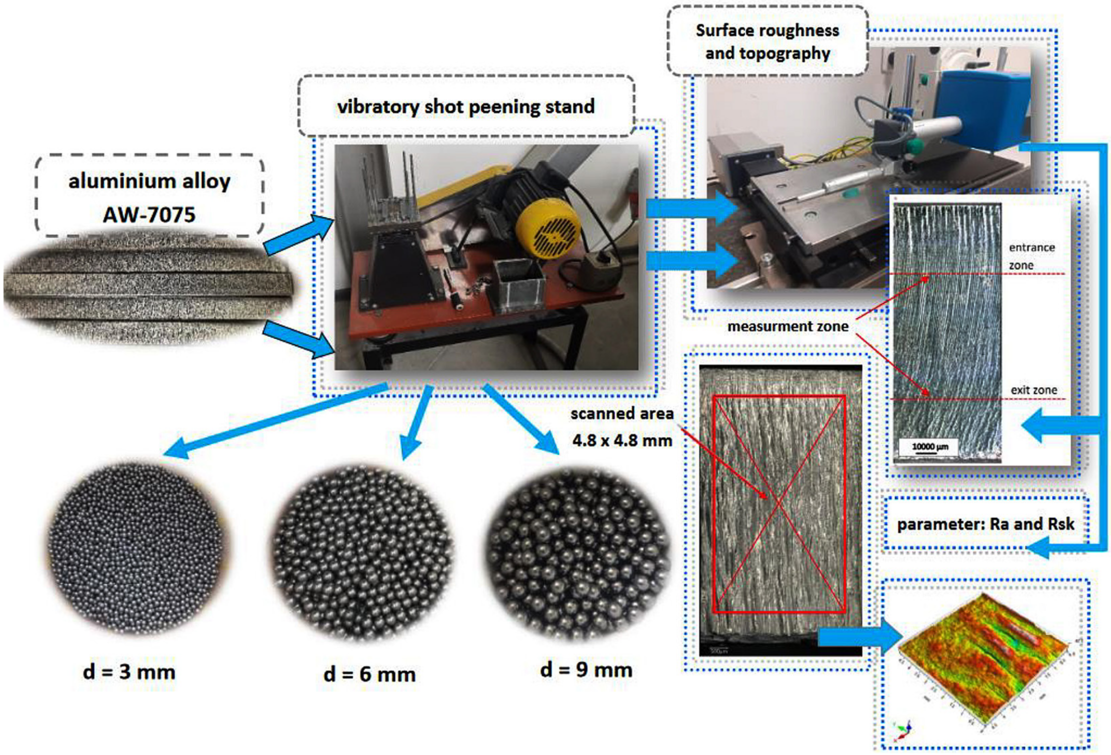



**Fig. 1.** Scheme of research methodology

roughness measurement zones is shown in Figure 1. The choice of the lower area for measuring surface roughness was due to the presence of a zone with varying roughness. The scan area was 4.8 x 4.8 mm and covered the entrance and exit zones.

The following 2D surface roughness parameters were analysed:

- Ra – arithmetic mean of the ordinates of the surface roughness profile,
- Rsk – profile asymmetry coefficient (skewness).

The above surface roughness parameters were selected for analysis owing to the engineering application of the Ra parameter and the possibility of assessing functional properties using the Rsk parameter.

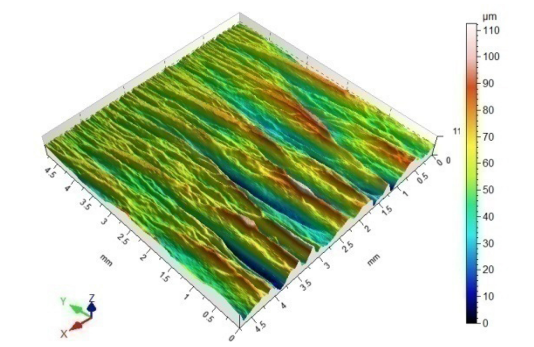
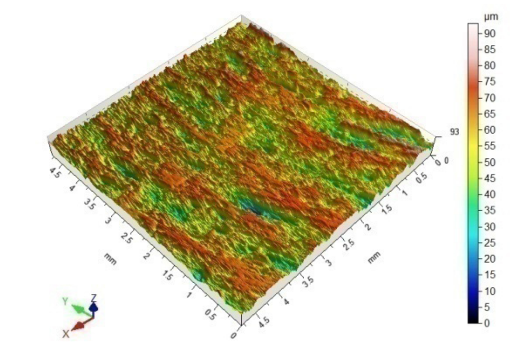
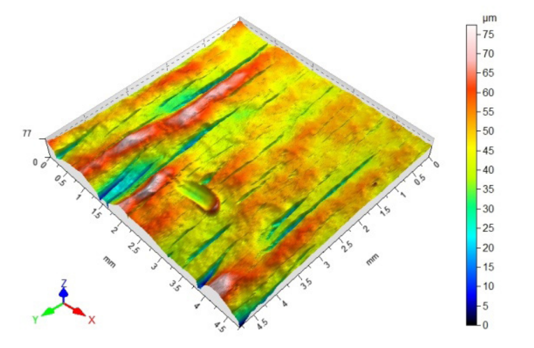
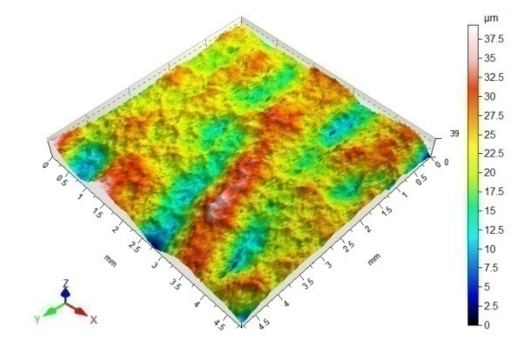
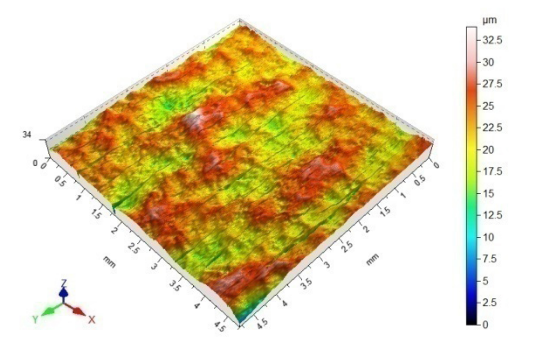
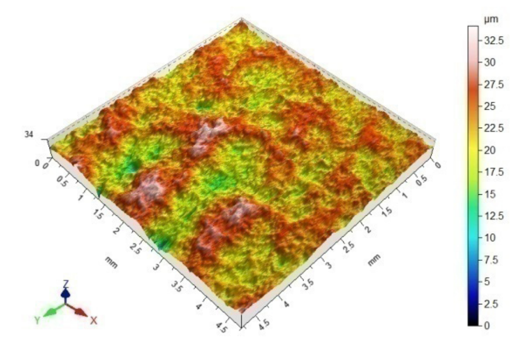
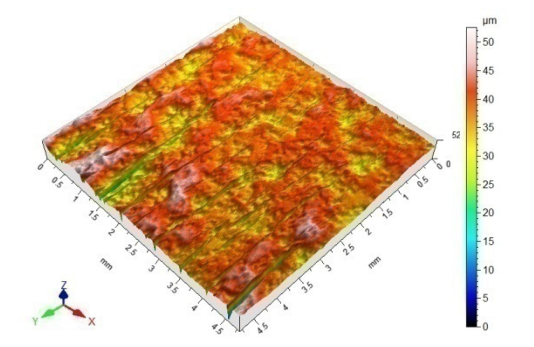
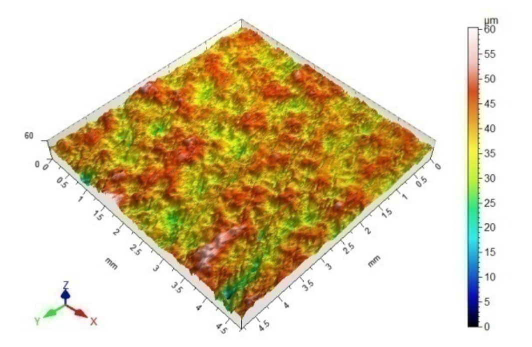
## RESEARCH RESULTS AND DISCUSSION

### Surface topography

Table 2 and Figure 2 present the surface topography and 3D parameters for the "raw" surface (after cutting with a laser and an abrasive water jet) and after VSP. The surface after laser cutting and AWJ shows the presence of striations, the arrangement of which in the entrance zone is parallel to the movement of the beam or stream. In the entrance zone, the striations are uniform, rectilinear with similar spacing. In the exit zone, the material begins to "escape" from the cutting kerf, which stimulates the formation of curvilinear striations. Higher elevations are visible on the surface after laser cutting, which leads to a higher value of the Sp parameter. A single vibratory shot peening operation does not completely "remove" the traces of microirregularities after the previous treatment. The striations formed by laser cutting and AWJ are flattened and deformed. Multiple impacts of the balls on the surface cause higher friction, which results in shearing the tops of the microirregularities. The smallest height parameters Sp, Sv and Sz are obtained for the surfaces after vibratory shot peening conducted with the 6 mm diameter balls. The balls with d = 3 mm are insufficient to deform the microirregularities remaining after the previous treatment. The contact area is too small to yield favourable results. Regardless of the VSP conditions used, the total height of the surface has a greater share of depressions than elevations, the Sv parameter is greater than Sp. Regardless of the pre-treatment used, the influence of the diameter of the balls on the surface topography and 3D parameters is the same. For the balls in the range of d = 3÷6 mm, there is a decrease in the analysed

3D parameters, while the use of the balls with d = 9 mm leads to an increase in the tested parameters (however, the 3D parameters are lower than after the previous treatment). This should be explained by the fact that despite the use of the balls having a larger contact area with the machined surface, the hardness of the material is a significant barrier to obtaining lower surface roughness.

**Table 2.** Surface topography and 3D parameters after single vibratory shot peening

| | Laser | Abrasive Water Jet Cutting |
|---|---|---|
| before |  |  |
| | Sa = 11.3 µm; Sz = 113 µm; Sp = 56.8µm; Sv = 55.8µm; Ssk = -0.088 ; Sku = 3.74 | Sa = 8.46 µm; Sz = 93.1 µm; Sp = 36.2µm; Sv = 56.9 µm; Ssk = -0.592 ; Sku = 3.39 |
| d = 3 mm |  |  |
| | Ssk = -0.645; Sku = 5.30 | Ssk = -0.194; Sku = 3.01 |
| d = 6 mm |  |  |
| | Ssk = -0.221; Sku = 3.79 | Ssk = -0.057; Sku = 3.31 |
| d = 9 mm |  |  |
| | Ssk = -1.34; Sku = 9.70 | Ssk = -0,409; Sku = 4.35 |

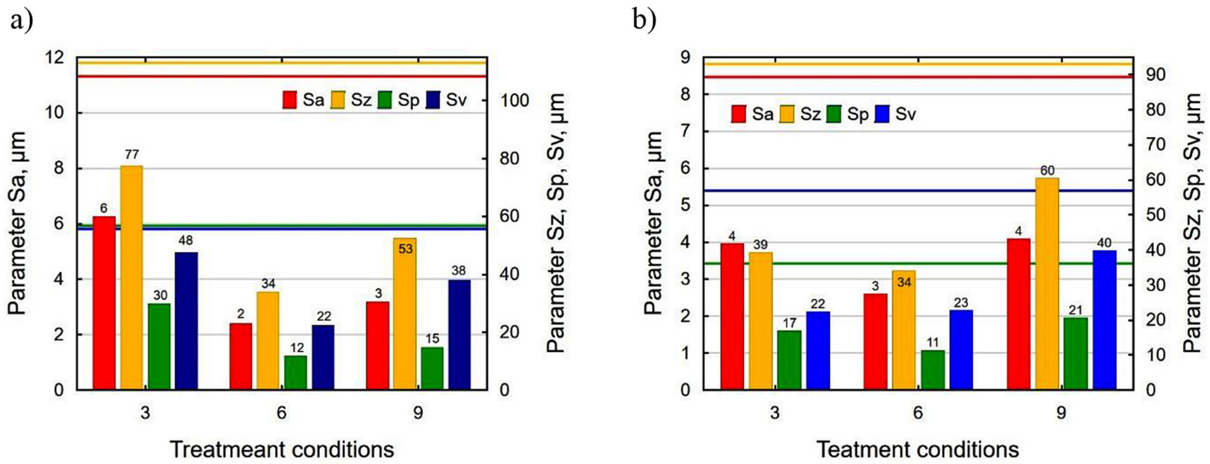
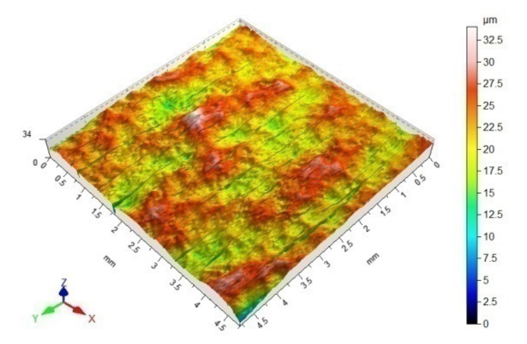
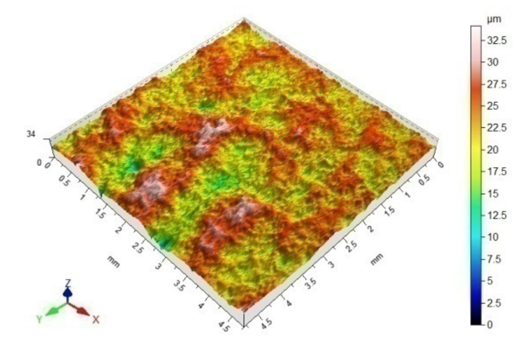
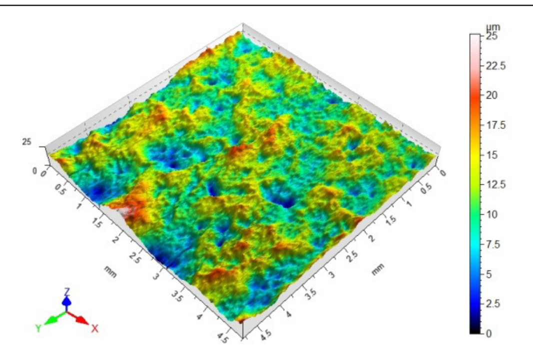
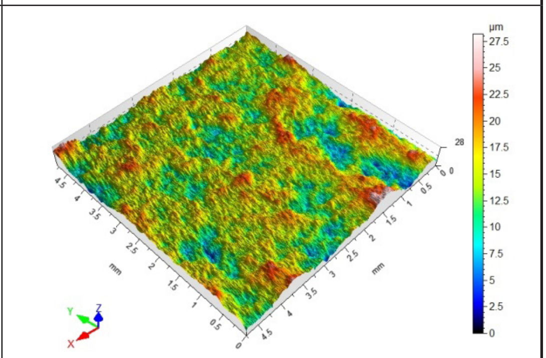



**Fig. 2.** The surface roughness parameter 3D of samples after laser cutting (a) and water-abrasive jet cutting (b) after VSP with balls of the different diameter (the solid line means the value of the parameter before VSP)

The use of an additional peening operation using 3 mm diameter balls causes the height of the microirregularities to be reduced, when compared to the VSP conducted with the 6 mm diameter balls (Table 3 and Figure 3). The height of the hills (parameter Sz) and the depth of the depressions (Sv) are reduced. After the RSP with the 3 mm diameter balls, the share of peaks and depressions in the total height of the elevations of the microirregularities is at a similar level. The use of the balls with d = 3 mm in the re-vibratory shot peening operation makes it possible to "smooth" the surface after vibratory shot peening conducted with the 6 mm diameter balls. As a result of using the balls with d = 9 mm in the re-vibratory shot peening operation, new depressions are knocked out on the surface (the Sv parameter increases). The absolute value of the Ssk parameter is higher, which means that the material is focused around the tops of the profile.

**Table 3**. Surface topography and 3D parameters after re-vibratory shot peening

| | Laser | Abrasive Water Jet Cutting |
|---|---|---|
| D = 6 mm |  |  |
| | Ssk = -0.221; Sku = 3.79 | Ssk = -0.057; Sku = 3.31 |
| D = 6 mm and d = 3 mm |  |  |
| | Ssk = 0.116; Sku = 3.41 | Ssk = -0.0002; Sku = 3.32 |

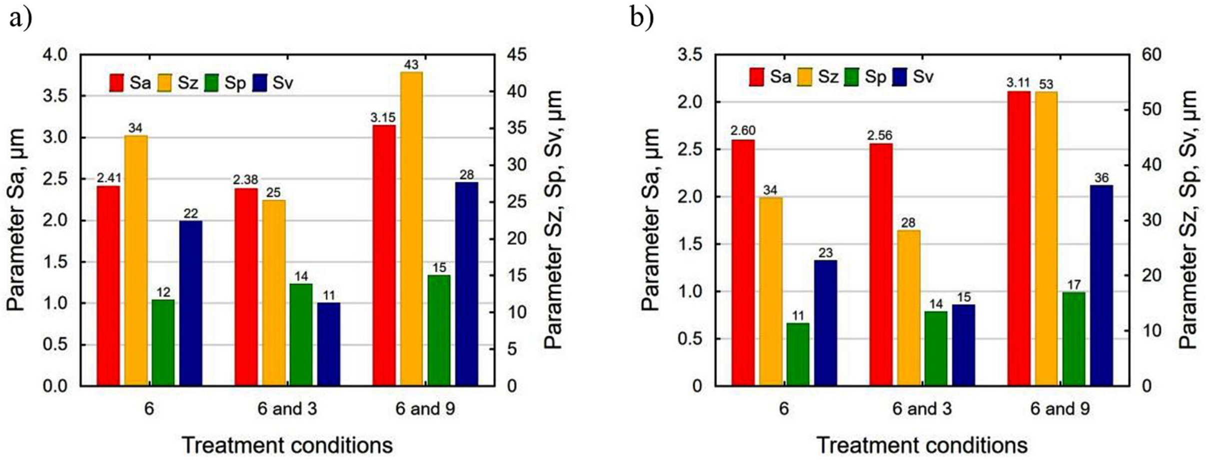



**Fig. 3.** The surface roughness parameters 3D of samples after laser cutting (a) and abrasive water jet cutting (b) after RVSP

The use of the re-vibratory shot peening operation for specific conditions brings favourable results in the reconstruction of the geometric structures of the surface of the elements after laser cutting and AWJ cutting that were obtained after single VSP, which is similar to the results reported in [19]. However, the changes in the surface roughness value are greater than those obtained in [19].

## Surface roughness

Figure 4a shows the impact of ball diameter on the Ra parameter for the elements treated by laser cutting first and then subjected to vibratory shot peening, while Figure 4b for the elements subjected to abrasive water jet cutting first and then to vibratory shot peening. The Ra parameter for the samples before vibratory shot peening is greater in the entrance zone than in the entry zone, with greater differences observed for the samples after laser cutting (approx. 25%). The larger values of the Ra parameter in the entrance zone result from the formation of uneven, curved and high-height striations in this area. After vibratory shot peening, the Ra parameter for the samples after laser cutting decreased by 85% to 90% in the entrance zone and by 71% to 91% in the exit zone. For the aluminium alloy AW-7075 components treated by AWJ first and then by VSP, these changes range from 56% to 85% in the entrance zone and from 68% to 84% in the exit zone, respectively. A comparison of these results with those obtained in previous studies on the finishing of workpieces after jet-erosion cutting demonstrates that the Ra parameter values were lower for the AW-7075 samples subjected to AWJ cutting after vibratory shot peening than after brushing [33] and after ball burnishing (BB)

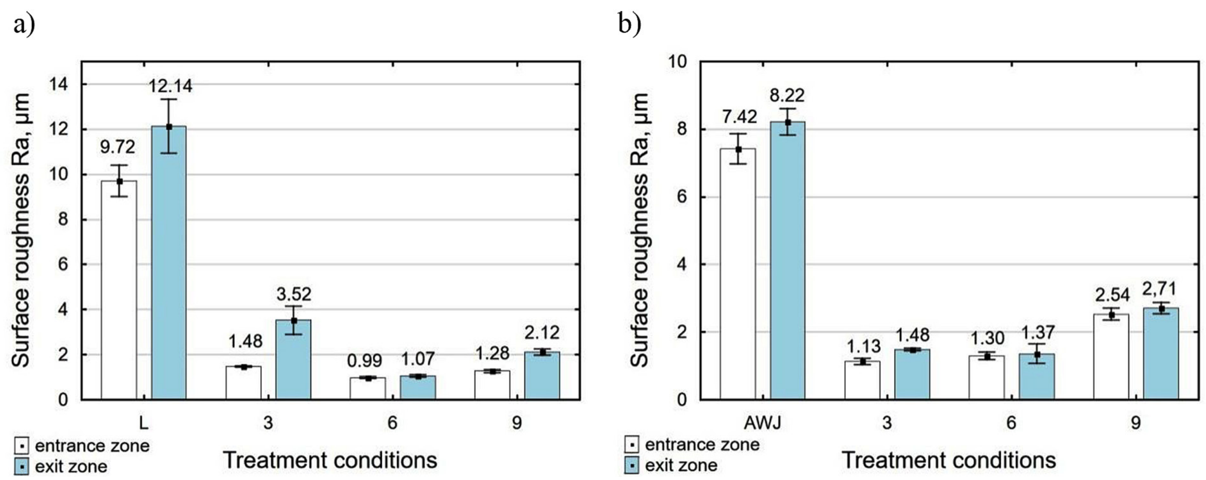



**Fig. 4.** The surface roughness parameter Ra of samples after laser cutting (a) and water-abrasive jet cutting (b) after VSP with balls of the different diameter

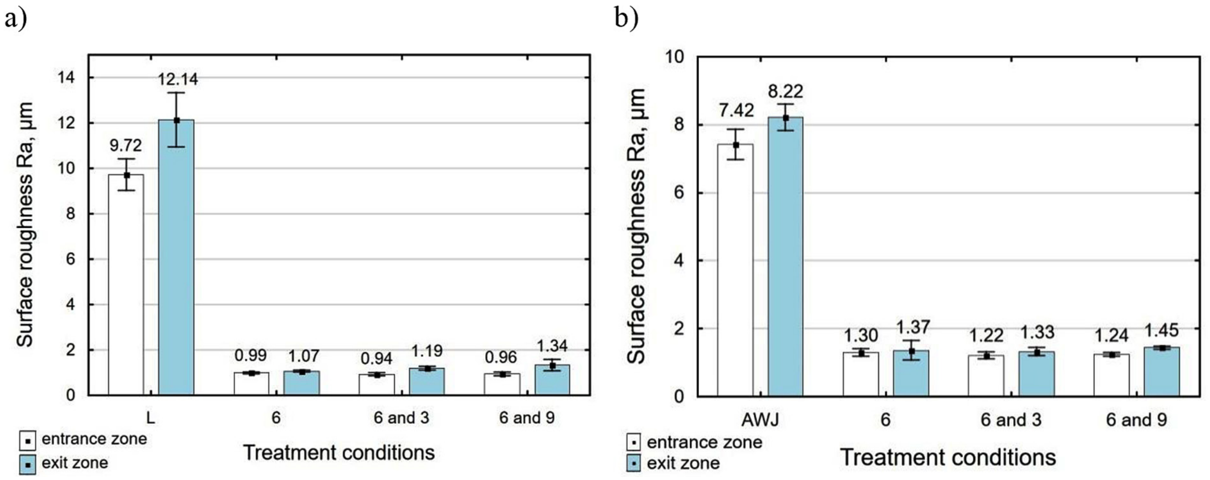



**Fig. 5.** The surface roughness parameter Ra of samples after laser cutting (a) and abrasive water jet cutting (b) after RVSP

for the C45 grade steel samples subjected to laser cutting [30]. After brushing the Ra parameter decreased by 15% to 29% in the entrance zone and by 2% to 28% in the exit zone, depending on the number of brushing passes [33]. However, depending on the diameter applied in the BB of the C45 grade steel after laser cutting, the surface roughness parameters decreased by 21% to 60% [30].

The use of an additional operation (re-vibratory shot peening) produces small changes in the Ra parameter value (Fig. 5). These changes are only visible in the entrance zone, for the samples after laser cutting and abrasive water jet cutting alike. Repeated VSP reduces the Ra parameter value in the entrance zone by 4% to 6% for the samples after laser cutting and by 5% to 7% for the AWJ-machined elements, when compared to the Ra value obtained after single vibratory shot peening conducted with d = 6 mm. On the other hand, in the entrance zone the analysed surface roughness parameter has a similar value as after vibratory shot peening conducted with the 6 mm diameter ball. The obtained changes in the Ra parameter value after RVSP are considerably smaller than those observed after the re-shot peening of AISI304 steel (the Ra parameter decreased by 18%) [23].

The increase in the deformation degree of the microirregularities is associated with a higher impact energy. The use of the balls with a larger diameter (d = 9 mm) makes it possible to flatten the surface roughness profile, especially in the exit zone. As a result of reducing the height of the microirregularities, the absolute value of the Rsk coefficient increases. The absolute value of the Rsk after VSP (Fig. 6) and RVSP (Fig. 7) is higher than after pre-treatment (laser cutting, abrasive water jet cutting). The negative value of

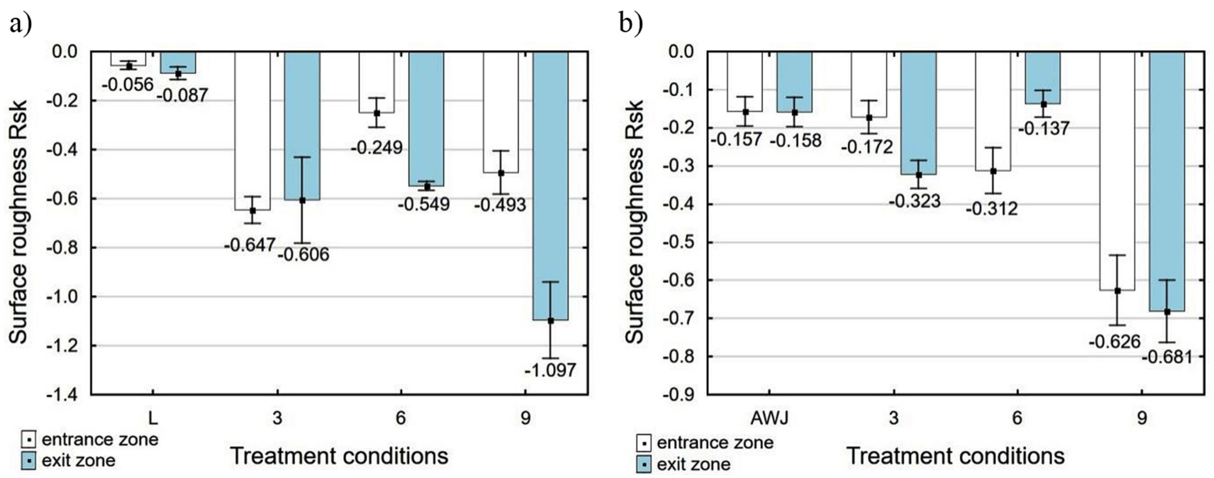



**Figure 6.** The surface roughness parameter Rsk of samples after laser cutting (a) and abrasive water jet cutting (b) after VSP with balls of the different diameter

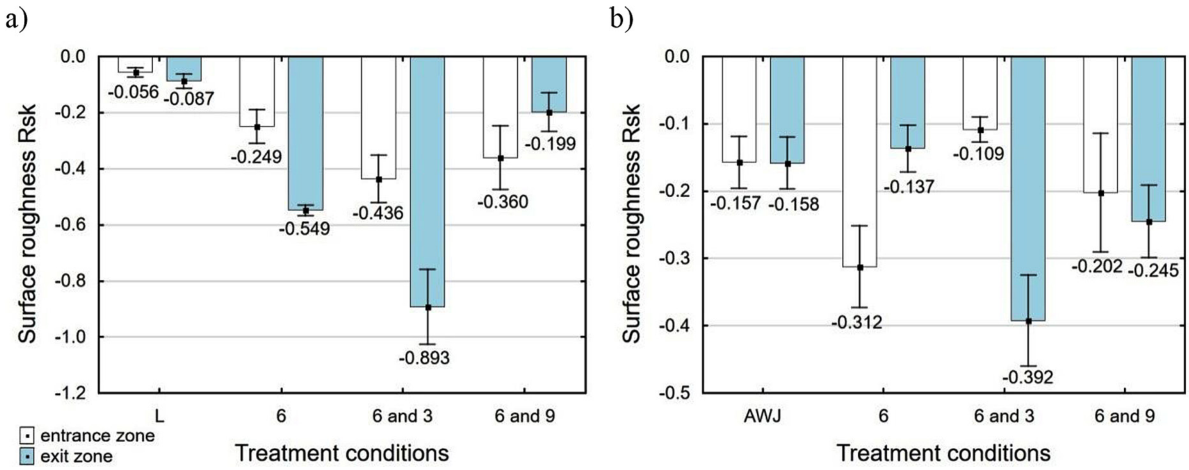



**Figure 7.** Influence of shot peening conditions (RVSP) on the surface roughness parameter Rsk of samples after laser cutting (a) and abrasive water jet cutting (b)

the skewness coefficient allows us to assume that the surface after VSP and RVSP will be characterized by a greater ability to transfer contact loads and will be less susceptible to tribological wear in the presence of a lubricant [34]. The Rsk coefficient values obtained after VSP are lower than those obtained after vibratory shot peening for stainless steel 1.4301 [32].

## CONCLUSIONS

The results of the study investigating the effect of vibratory shot peening and re-vibratory shot peening on the geometric structure of the surface of samples after laser cutting and abrasive water jet cutting lead to the following conclusions:

- the surface roughness (parameter Ra) of aluminium alloy AW-7075 samples after vibratory shot peening is from 3.0 to 6.5 times lower than that obtained after AWJ and from 3.5 to 11 times lower than after laser cutting; the difference in the value of surface roughness parameters between the entrance and exit zones is reduced equally,
- the use of an additional VSP (re-vibratory shot peening) reduces the Ra parameter value in the entrance zone by 4% to 7%, when compared to the value obtained after single vibratory shot peening with d = 6 mm,
- the use of single VSP does not completely remove the striations that were formed on the surface of the sample as a result of the cutting process; they are flattened and their height is reduced. The re-vibratory shot peening operation causes a "more complete" smoothing of the surface after SP conducted with 6 mm diameter balls. The use of balls with a diameter of 3 mm causes that the share of Sp and Sv in Sz is at a similar level,
- the negative skewness coefficient Ssk (significant value Sk = -0.902) obtained after re-vibratory shot peening (for d = 3 mm), provided that Sv>Sp, allows us to conclude that the friction on the surface will be reduced in the presence of a lubricant, which is in accordance with [34].

The results of this study investigating the influence of VSP and RVSP parameters on the geometric structure of the surface of elements made of aluminium alloy AW-7075 confirm the validity of this work. However, the results obtained after re-vibratory shot peening are not entirely satisfactory (changes in the values of the analysed surface roughness parameters are relatively small), which prompts further work on the use of this technology. For higher effectiveness, it is necessary to increase the intensity of vibratory shot peening, which can be achieved by using a longer vibratory shot peening time. The process of laser cutting and water jet cutting are two different processes in terms of the thermal phenomena that accompany them. In this work, the effect of heat, which could be the subject of further publications, was not investigated.

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