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INFLUENCE OF SINGLE-STAGE AND DUPLEX SHOT PEENING ON SURFACE ROUGHNESS AND RESIDUAL STRESSES IN Al Mg5 Mn1 Sc0,8 Zr0,4 ALLOY

Conventional shot peening (SP) is cheap surface treatment widely used to enhance fatigue life of mechanical components [3,4]. Basically, it is shooting small particles (shots) on the surface of the sample. However, the process itself is so complex that a lot of companies are not able to optimally employ it due to the amount of parameters that must be controlled all at the same time.

The duplex process consists in two stages of shot-peening treatment. The first one consist of shot-peening with spherical cast steel shots or cut wire shots. During the second stage the samples processed in stage one were subject to shot-peening with glass beads.

In this work, RSA-501 aluminium alloy was shot peened using shots of different material and diameter and tested using a measurement of residual stresses and surface roughness. Tests and studies conducted so far on RSA-501 aluminium alloy demonstrate that bombardment by a treatment medium in the form of glass beads or shots of various shapes and diameters induces permanent plastic deformation of the surface layer. The roughness achieved after the shot-peening process was determined for each treatment medium. The largest value of Ra parameter was achieved for cut wire shots and this result is consistent with the above-mentioned theoretical knowledge. This medium is the most aggressive one to the surface being treated primarily due to the sharp edges of shots. The duplex process was successful in obtaining higher values of compressive stresses in surface layer than values achievable in conventional single-stage shot peening process.

Keywords: shot peening, double shot peening, residual stresses, roughness

1. Introduction

Industrial branches like automotive and aerospace industry put great efforts to reduce the production costs together with increasing strength properties of the components [1-7]. So the trend is to replace the heavy parts with some another material such as light alloys [8,9]. The problem of these alloys is their poor mechanical properties. Thus, there is a need for some enhancement, which could be accomplished, among others, by a surface treatment technique called shot peening.

Conventional shot peening (SP) is cheap surface treatment widely used to enhance fatigue life of mechanical components [3,4]. Basically, it is shooting small particles (shots) on the surface of the sample. However, the process itself is so complex that a lot of companies are not able to optimally employ it due to the amount of parameters that must be controlled all at the same time.

The shots are usually small, hard ceramic or metallic beads with a diameter typically tenths of millimetre. Bombardment by these particles causes plastic deformation, which results in compressive residual stress field near the surface [2,10]. Of course it is accompanied by the increment in surface roughness, which can decrease the fatigue life, because it promotes crack nucleation and their further propagation [4,11]. But overall, indeed, the positive effects outbalance the negative ones.

There are some studies from recent years in literature dealing with shot peening with different parameters and conditions performed on aluminium alloys [2-4,10-34]. The favourable effect of SP treatment of structural elements exposed to the corrosive environment was determined by [12-14], although roughened surfaces after SP have a higher specific surface and thus it increases corrosion potential [15]. There are studies on severe shot peening [16], fine particle shot peening [17,18], comparing conventional SP with another surface treatments [2,15,19-21,35] and multiple re-shot peening [22].

Gao [2] concluded that for as-machined specimens fatigue cracks initiate at the surface, while for both the laser- and shot-peened specimens the fatigue cracks form in the subsurface layer beneath the compressive residual stress field. Local stress concentrations can be found at roughen areas, which implies that surface roughness is important in predicting fatigue resistances [22]. Enhancement in fretting fatigue life [19,22], plain [10,24] and multi-axial [25] fatigue resistance, and better fatigue properties [2,11,15,19-21] can be found after shot peening on aluminium alloys. The effect of SP on fatigue life can be summarized in a way that it induces compressive residual stress and strain-hardening that suppress crack propagation, and surface roughening that accelerates crack formation and early propagation [26].

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Vázquez et al. [19] published that SP increases fretting fatigue life more, when the surface roughness is not modified after treatment by polishing. From [15] comparison between SP, ball-burnishing (BB) and electrolytically polished (EP) reference condition, it is seen that SP has the highest roughness, while characteristically different surface roughness was obtained by BB, which was almost as low as in the EP reference condition. Increasing SP Almen intensity resulted proportionally in greater residual stress, rougher surface and also the microhardness was higher [11,15]. Another study [20] compared SP, BB, EP, ultrasonic shot peening (USP) and laser peening without coating (LPwC). It was found out that roughness values of LPwC and SP are comparable, while BB resulted in much lower roughness. Values of USP were in the middle. In contrast, Luong and Hill [21] used different parameters for SP and LP, and reported roughness of SP surface more than 8 times that measured for the AM condition. Whereas roughness of LP surfaces was similar to the AM surface, except for significant increase in waviness of LP treated specimens above the AM condition.

From the facts mentioned above, it is obvious that the surface modification plays a very important role not only in fatigue life, but also in tribological behaviour of mechanical components, and it is essential to investigate the surface more precisely. In this study, RSA-501 aluminium alloy was shot peened using shots of different material and diameter and tested using measurement of residual stresses and surface roughness.

2. Test material

For tests the experimental aluminium alloy was used, having the chemical composition of Al Mg5 Mn1 Sc0,8 Zr0,4 and properties specified in Table 1.

This material very advantageously combines remarkable strength properties and good plasticity. Apart from the magnesium content, the presence of scandium is responsible for this effect. A small addition of this element boosts the strain hardening effect [37]. Machinability can be qualified as easy. Application areas include machine building, racing, sport equipment, fasteners, aerospace and orthopedics.

In total, 28 specimens were tested. The specimens were prepared by cutting from ϕ50 mm round bar. All specimens were grounded, then subject to relief annealing and afterwards to conventional and duplex shot peening.

3. Methodology

The experiment consisted in conducting SP treatment using various media, i.e. shots of different material, shape and diameter (see Table 1). The single-stage SP treatment was carried out for four types of hardening media made of various materials and with various shapes and diameters, namely:

- cast steel spherical shots with a diameter of 0.5 mm (S230 according to FEPA standard), 1.0 mm (S390), and 1.8 mm (S660)
- cast iron spherical shots with a diameter of 0.8 mm (S330) and 1.4 mm (S550)
- wire cut shots with a diameter of 1.2 mm
- glass beads with a diameter of 0.6-0.8 mm

Besides the type and size of shots, the process variables included the pressure and distance between the nozzle and specimen. The inclination angle of shot beam was 90° and remained constant for all processes.

Further, the selected specimens were subject to duplex-type shot peening process consisting of two stages. In the first stage the specimens were shot peened by spherical cast steel shots with a diameter of ϕ0.5 mm or shots cut from ϕ1.2 mm wire; the pressure was equal to 7 bars and the nozzle-specimen distance was 150 mm. During the second stage the same specimens were peened by using ϕ0.6-0.8 mm glass beads using the following parameters: pressure – 3 bar, nozzle distance – 150 mm (Table 2).

Both single-stage and duplex peening processes were conducted in a pneumatic injector-type sandblasting machine manufactured by the CONTRACOR Company.

Upon completion of the single-stage and duplex shot peening process, the specimens were tested for surface roughness and residual stresses. The surface roughness was measured by using the Hommel Werke profile measurement gauge, type T8000, with Turbo Wave 7.35 software. The measurements were carried out in compliance with the PN-ISO 4288:1998 standard in five points as shown in Fig. 1.

TABLE 1

Properties of RSA-501 aluminium alloy [36]

		Physical properties					Mechanical properties								
Condition	Typical composition	Density [gr/cm^3]	Thermal Expansion [10^{-6}/K]	Stiffness [Gpa]	Specific Stiffness [Gpa/(g/cc)]	Thermal Conductivity [W/m.K]	Ultimate Tensile Strength [Mpa]	Yield Strength [Mpa]	Elongation [%]	Hardness [HB]	Fatigue [Mpa]	Fracture toughness	Corrosion resistance	Weldability	Specific Yield Strength [E/p]
AE	**Al Mg5 Mn1 Sc0,8 Zr0,4 (Scalmalloy)**	2.65	23	70	26	140	575	525	12	160	400	35	++++	++++	198.1

TABLE 2

Process parameters

Speci-men No.	Type of medium							Pressure		Nozzle-specimen distance	
	Cast steel spherical shots			Cast iron spherical shots		Glass beads	Cut wire shots				
	0.5 mm (S230)	1.0 mm (S390)	1.8 mm (S660)	0.8 mm (S330)	1.4 mm (S550)	0.6 – 0.8 mm	1.2 mm	3 bar	7 bar	150 mm	300 mm
1	X							X		X	
2	X							X			X
3	X								X	X	
3 duplex								X		X	
4	X								X		X
5		X						X		X	
6		X						X			X
7		X							X	X	
8		X							X		X
9			X					X		X	
10			X					X			X
11			X						X	X	
12			X						X		X
13				X				X		X	
14				X				X			X
15				X					X	X	
16				X					X		X
17					X			X		X	
18					X			X			X
19					X				X	X	
20					X				X		X
21						X		X		X	
22						X		X			X
23						X			X	X	
24						X			X		X
25							X	X		X	
26							X	X			X
27							X		X	X	
27 duplex								X		X	
28							X		X		X

* The duplex process consisted in two-stage shot peening treatment. In the first stage specimen No. 3 was treated with spherical cast steel shots, and specimen No. 27 was treated with wire cut shots – both with the aim to induce compressive stresses in the technological surface layer. Then, the second stage of treatment was carried out consisting in shot-peening with glass spheres, in order to smoothen the surface.

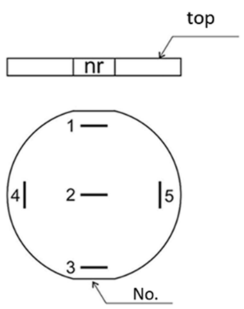

Fig. 1. The specimen with surface roughness measurement points

For measuring residual stresses the X-ray method was employed. The measurements were carried out by using the PROTO iXRD diffractometer with the following settings:

Cr tube, Kα1 band, tube voltage 20 kV, tube current 4 mA, Bragg angle 156.31° (reflections from the 222 family of lattice planes), oscillation around beta angle within the range of 3°, LPA correction, and 2 mm aperture. The position of obtained diffraction peaks was approximated by Cauchy function. Elastic constants were assumed according to the computer application database as follows: (1/2)S2 = $18.56\cdot10^{-6}$ MPa^{-1} and S1 = $4.79\cdot10^{-6}$ MPa^{-1}. Results were presented in numerical values of stress expressed in MPa.

4. Results and discussion

4.1. Surface roughness

All untreated specimens featured surface roughness of R_a = 0.08 µm. As a result of specimen deformation by various abrasives, significantly higher values of surface roughness were obtained.

Figure 2 presents the measured values of surface roughness R_a for the pressure of 3 bar, depending on the nozzle distance and the diameter of cast steel spherical shots. It can be observed that there is a rising behaviour of R_a for both nozzle distances, i.e. the higher R_a the bigger the shot diameter. The otherwise known descending tendency of R_a with the increasing nozzle distance to the treated surface is also evident.

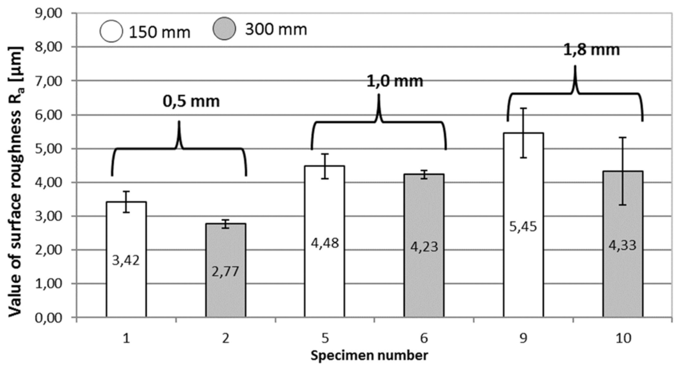

Fig. 2. Spherical cast steel shots – behaviour of surface roughness for the pressure of 3 bar as a function of nozzle distance and diameter of treatment medium

Figure 3 shows the graph of R_a values for the pressure of 7 bar as a function of nozzle – specimen distance and the diameter of spherical cast steel shots. Similarly to the graph in Fig. 2, the surface roughness depends on the diameter of the treatment medium in the rising manner, i.e. R_a becomes greater when greater diameter shots are used for peening. Additionally, for this pressure the difference in R_a as a function of nozzle distance is smaller than for 3 bar pressure.

Figures 4 and 5 present the behaviour of surface roughness after treatment with spherical shots as a function of pressure for

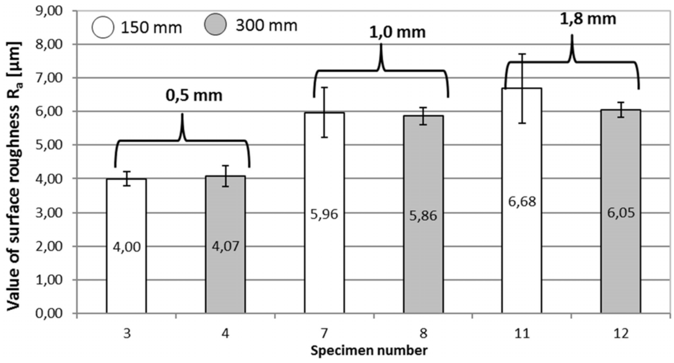

Fig. 3. Spherical cast steel shots – behaviour of surface roughness for the pressure of 7 bar as a function of nozzle distance and diameter of treatment medium

nozzle depending on the specimen distance. As a rule SP treatment performed at higher pressures leads to higher roughness values. Such behaviour occurs for each diameter of cast steel shots and for each nozzle distance. The highest R_a value was obtained for ϕ1.8 mm shots and 7 bar pressure, whereas the lowest R_a value was obtained for ϕ0.5 mm shots and 3 bar pressure for both nozzle distances.

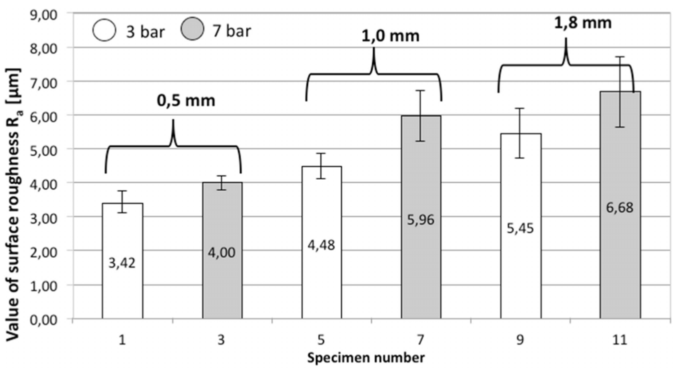

Fig. 4. Spherical cast steel shots – behaviour of surface roughness for the nozzle-specimen distance of 150 mm

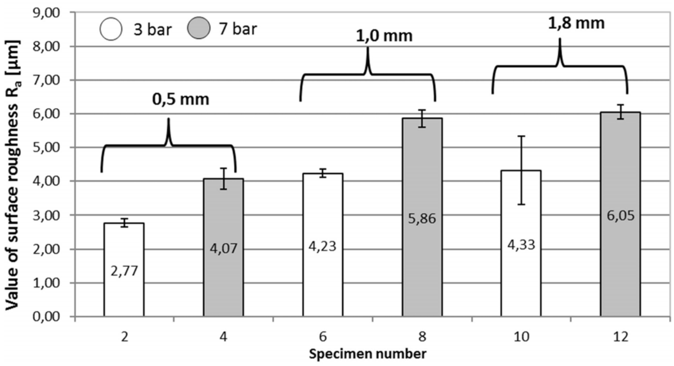

Fig. 5. Spherical cast steel shots – behaviour of surface roughness for the nozzle-specimen distance of 300 mm

The graphs of surface roughness R_a as a function of nozzle distance and diameter of spherical cast iron shots are presented below in Fig. 6 (for the pressure of 3 bar) and Fig. 7 (for the pressure of 7 bar).

In Fig. 6 the increasing tendency of R_a parameter as a function of distance between the nozzle and specimen surface can be observed. However, in this case the surface roughness depends on the medium diameter oppositely than for SP treatment with spherical cast steel shots.

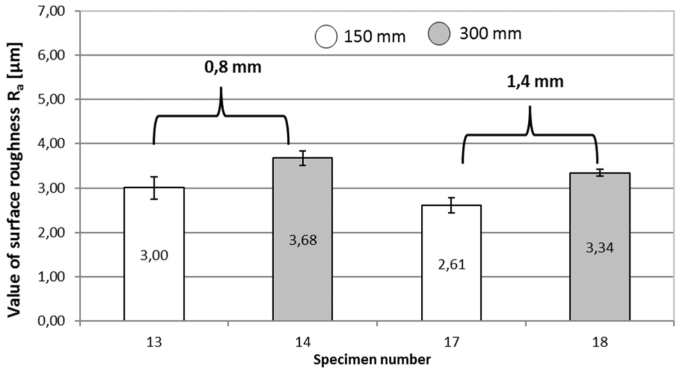

Fig. 6. Spherical cast iron shots – behaviour of surface roughness for the pressure of 3 bar as a function of nozzle distance and diameter of treatment medium

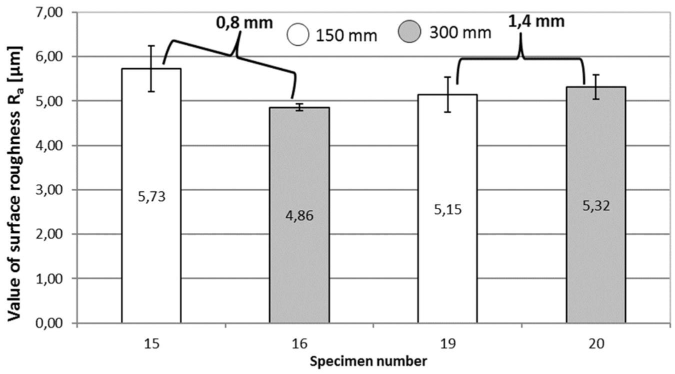

Fig. 7. Spherical cast iron shots – behaviour of surface roughness for the pressure of 7 bar as a function of nozzle distance and diameter of treatment medium

At the pressure of 7 bar (Fig. 7) there is no clear influence of the nozzle distance on the surface roughness, and if any, it is even opposite as compared to the case with 3 bar pressure (Fig. 6). Such behaviour is caused by uneven coverage of treated surface resulting from scaling the industrial technology to laboratory testing conditions. The specimens were relatively small as compared to the shot beam. For the shot diameter of 0.8 mm the observed roughness is smaller for greater nozzle-specimen distance, while for 1.4 mm diameter this dependency is reverse.

The measurement results show than at 7 bar pressure the surface roughness is almost 1.5 times higher than the roughness obtained at 3 bar pressure (Figs. 8,9). Further, when the bigger diameter shots were used, no increase in surface roughness was observed.

The obtained values of surface roughness R_a as a function of pressure and of nozzle distance and diameter of the peening medium in the form of glass beads are presented in Figure 10. For this SP treatment medium the obtained values of surface

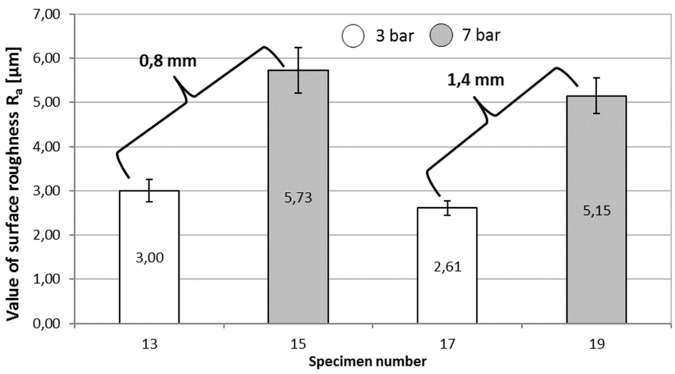

Fig. 8. Spherical cast iron shots – behaviour of surface roughness for the nozzle-specimen distance of 150 mm

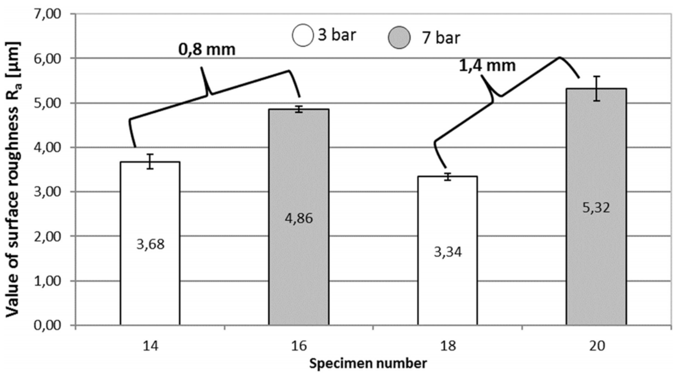

Fig. 9. Spherical cast iron shots – behaviour of surface roughness for the nozzle-specimen distance of 300 mm

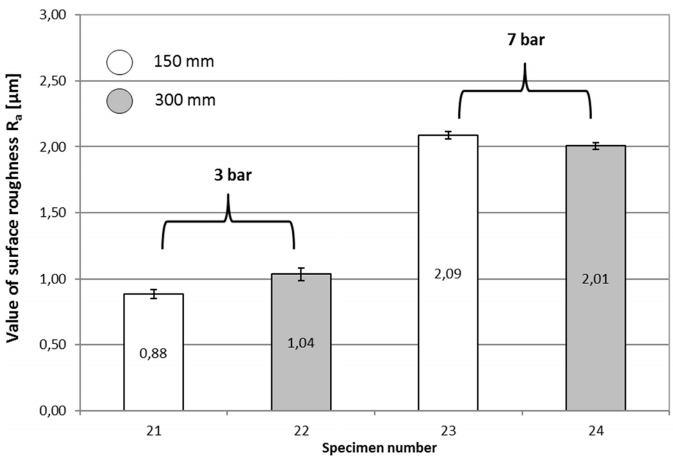

Fig. 10. Glass beads – behaviour of surface roughness for the different pressure and the nozzle-specimen distance

roughness were much lower than the values obtained for cast steel or cast iron shots.

It is worth noticing that in the case of this medium the distance between the nozzle and specimen surface has no significant effect on surface roughness at constant pressure (Fig. 10), while at the constant nozzle – specimen distance the increase of surface roughness was observed. For the pressure of 3 bar (Fig. 10) the resulting surface roughness R_a was more than two times less than for the pressure of 7 bar.

Interesting results were obtained for cut wire shots (Fig. 11). Due to the shape of medium particles the obtained values of surface roughness R_a were higher than obtained for all other hardening media used for testing. However, a strong dependence of roughness on pressure was observed (Fig. 11). At higher pressure the post-treatment R_a values were several times higher than for lower pressure. As far as the nozzle-specimen distance is concerned, no clear influence on the obtained R_a values was observed.

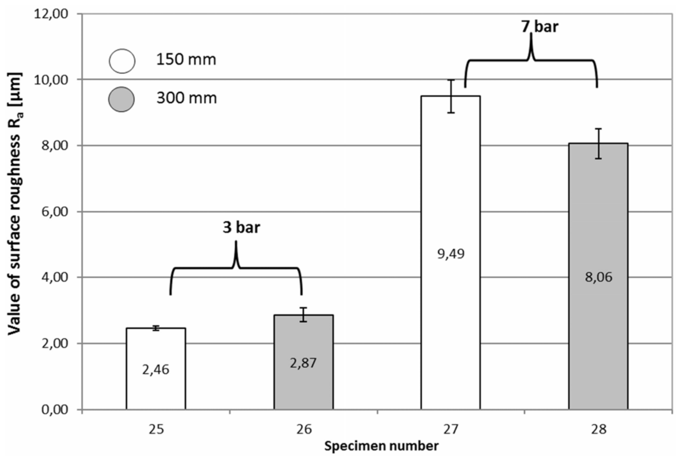

Fig. 11. Cut wire shots – behaviour of surface roughness for the different pressure and the nozzle-specimen distance

One can easily see (Figs. 2-11) that the value of R_a parameter is definitely highest for cut wire shots, i.e. the sharp-edge shots and for the pressure of 7 bars. The next highest value of R_a was measured for specimens treated with the largest spherical shots (ϕ1.8 mm) at the pressure of 7 bar. On the other hand, the smallest value of R_a was obtained for the specimen treated with glass beads at the pressure of 3 bar.

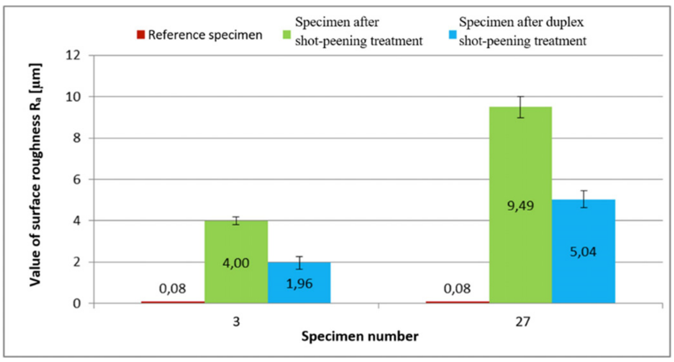

Fig. 12. Comparison of Ra values for specimens after duplex treatment

The results of surface roughness measurements for samples after duplex type shot-peening are presented in Fig. 12. As it can easily be seen, the value of surface roughness R_a drops significantly (by about 50%) after both duplex-type processes. This effect results from glass beads which smoothen the surface being treated.

4.2. Residual stresses

The behaviour of residual stresses as a function of nozzle-specimen distance is shown in Fig. 13. The maximum value of compressive stresses in the reference specimen amounted to –68 MPa and was achieved on the specimen surface. These stresses result from initial grinding of specimen surface prior to shot-peening treatment.

The use of cut wire shots in single-stage processes resulted in the introduction of the lowest compressive stresses to the specimen surface, amounting to about –30 MPa. At the same time, the least satisfactory result was obtained in case of maximum compressive stresses in the hardened zone – at the depth of 150 and 250 μm the stresses amounting to about –250 Mpa were observed. It is the lowest value of compressive stresses from among the three specimens subject to tests. For the spherical cast steel shots the maximum compressive stresses of about –320 MPa were found at the depth of 150 μm below the surface. At the surface itself the stresses were at the level of approximately –120 MPa. The highest value of compressive stresses was achieved in case of treatment with glass beads (about –180 MPa). However, the maximum compressive stresses in the strain-hardened zone of the surface layer were slightly lower than the ones obtained for spherical cast steel shots. The depth of strain-hardened zone is also important information. In the tested specimens the maximum compressive stresses occur at the depth of about 150 μm from the surface.

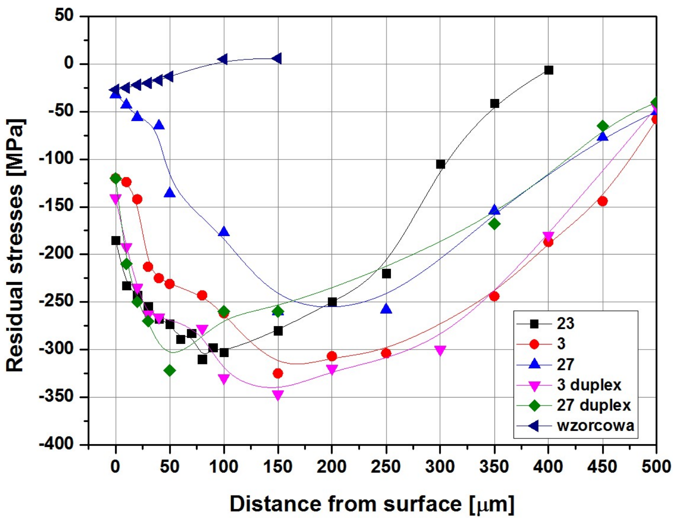

Fig. 13. Stresses as a funcion of distance from the surface

The tests of residual stresses in specimens subject to duplex-type shot peening proved that after treatment with a second medium in the form of glass beads, more advantageous compressive stresses were obtained following the duplex process. In case of the specimen treated with cast steel spherical shots subjecting it subsequently to the duplex process resulted in obtaining definitely higher compressive stresses in the technological surface layer, i.e. greater by 15 up to 100 MPa on average. For this specimen the highest (by about 100 MPa) increase of compressive stresses was obtained at the depth range of ca. 100 μm up to 350 μm.

Subjecting the specimen previously shot-peened with cut wire shots to subsequent duplex process showed that stresses change most in the zone extending from the specimen surface to the depth of about 150 μm. The value of residual stresses increases from about 100 MPa to the level of above 200 MPa.

At depths exceeding 150 μm the influence of glass beads used as the second strain-hardening medium is not so significant anymore.

5. Summary and conclusions

Tests and studies conducted so far on RSA-501 aluminium alloy demonstrate that bombardment by a treatment medium in the form of glass beads or shots of various shapes and diameters induces permanent plastic deformation of the surface layer. The roughness achieved after the shot-peening process was determined for each treatment medium. The largest value of Ra parameter was achieved for cut wire shots and this result is consistent with the above-mentioned theoretical knowledge. This medium is the most aggressive one to the surface being treated, first of all due to the sharp edges of shots. Regardless the pressure and nozzle distance, the least roughness values were achieved for glass beads which turned out to be least aggressive to the surface of aluminium alloy.

Comparing the obtained results of surface roughness measurements with the results published by Benedetti et al. in article [20] it can be stated that they are very close. In that study the Al 7075 alloy was used, and the closest parameters used were the distance between the nozzle and the treated surface (90 mm) and pressure (8 bar). For S270 shots the value of R_a at the level of 4.45 μm was obtained. This value slightly differs from our result of nearly 4 μm for S230 shot at the pressure of 7 bar and nozzle distance of 150 mm.

In most cases the results of measurements carried out using the diffractometer for various specimens confirm the theoretical assumptions quoted earlier. The highest value of compressive stresses is ensured when spherical cast steel shots are used, while the lowest one when SP treatment is carried using cut wire shots.

In comparison to study [24] referred to above, higher values of compressive stresses were obtained. In that study the maximum compressive stresses at the level of –208 MPa were obtained for surface treatment with S270 shots at the settings specufued above. This result is worse than the one obtained in this study for S230 shots. The measured values of residual stresses (Fig. 13) indicate that the maximum compressive stresses amount to about –325 MPa, which is arguably caused by using smaller diameter shots.

Improvement in properties of technological surface layer was observed both after conventional single-stage SP process and the duplex process combining two different treatment media.

Due to the duplex process it was possible to obtain a technological surface layer featuring values of compressive stresses higher than in case of the traditional single-stage shot peening process. The value of compressive stresses is the key parameter crucial for the improvement of processed elements' strength. Additionally, as a result of treatment with glass beads, the surface with significantly reduced value of roughness R_a was obtained. Thus, the technological surface layer featuring better strength properties got an additional advantage in the form of more smooth surface, which in turn broadens the spectrum of applications of the processed elements.

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