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Influence of Grinding on Residual Stress Measurements of Shot Peened Aluminium Alloy AA7075

Sebastjan Žagar* – Roman Šturm
University of Ljubljana, Faculty of Mechanical Engineering, Slovenia

The present study aims to investigate the influence of grinding on shot peened (SP) aluminium alloy 7075 by means of residual stresses. The aluminium alloy was subjected to homogenisation annealing at 475 °C for 2 h, followed by quenching in water to room temperature. After that, the surface was shot peened with different Almen intensities and at different coverages to obtain compressive residual stresses in the surface layer of the material. The grinding operation is then followed to reduce the surface roughness and also to increase corrosion resistance. The first method used for measuring residual stresses was a semi-destructive blind-hole drilling method and the second was a non-destructive X-ray diffraction method. The resulting residual stress profiles reveal that residual stresses throughout the surface layer of all shot peened specimens are of a compressive nature. The highest value of residual stress were obtained after shot peening with 16A and a coverage of 200 %, i.e., –377 MPa at a depth of 250 mm. However, regardless of any shot peening parameters, the compressive residual stresses in the specimens are, after reaching maximal values, directed towards the tensile area with a very similar gradient.
Keywords: AA7075, shot peening, microhardness, roughness, residual stresses, blind-hole drilling, X-ray diffraction

Highlights
- *The influence of shot peening on a quenched aluminium alloy was researched.*
- *Residual stresses according to different Almen intensities were compared.*
- *Differences in residual stresses were observed in the depth of hardening and in the value of compressive residual stresses.*
- *Two measurement techniques for residual stresses were presented and the results were compared.*

0 INTRODUCTION

Aluminium alloys series 7xxx containing zinc, magnesium and copper, as the main alloy elements, are characterised by high ultimate tensile strength (UTS) between 350 MPa and 650 MPa, depending on the state of the alloy. For comparison, the extruded profiles from 6xxx alloys after heat treatment show the UTS at levels of 160 MPa to 340 MPa. Due to its high specific strength, formability, corrosion resistance, resistance to stress corrosion cracking, lightweight and wide application, the aluminium alloy 7075 is widely used in automotive and aerospace industries [1] to [4]. However, these alloys generally have poor ductility and low fracture strength in the as-cast condition, and extensive processing, which includes a combination of heat treatment and hot-cold working, is required to improve the mechanical properties [5].

González et al. [6] investigated different shot peening treatments with conventional and severe parameters, which were performed on an aluminium 6063 alloy in order to assess the differences induced in the microstructure of the surface layer and to evaluate their effects on fatigue behaviour. The obtained results evidence the notable influence of shot peening parameters on the surface layer microstructure, which simultaneously influence fatigue behaviour.

Jamalian and Field [7] carried out a microstructural analysis of an AZ31 Mg alloy, which revealed a direct relation between the thickness of the ultra-fine grained layer and severe shot peening parameters, with each of them having a distinct effect on grain size. Furthermore, microhardness tests demonstrated how pressure and shot size control fine grains at the surface. Tensile test results revealed that the best mechanical properties were obtained by maximum shot size and pressure at minimum processing time. Nam et al. [8] investigated the effects of four peening parameters on microhardness and residual stress of AA 2124-T851. To verify the validity of the optimal conditions obtained from experimental results, metallurgical analyses of the shot-peened aluminium alloy were conducted with respect to hardness, residual stress, surface morphology, X-ray diffraction (XRD) analysis and surface roughness. They concluded that shot peening induces plastic deformation, increases surface hardness and introduces significant levels of compressive residual stress. Under optimal peening conditions, the average microhardness and compressive residual stress are ~13 % higher than that of the unpeened sample.

Žagar and Grum [9] studied two types of aluminium alloys, EN AW 2007 and EN AW 6082, treated by shot peening, in which the surfaces of the metals were subjected to cold deformation

*Corr. Author's Address: University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, sebastjan.zagar@fs.uni-lj.si

under different treatment conditions. The treated surfaces were studied in terms of surface integrity at macro- and microscopic levels, including the surface roughness, microhardness profiles and residual stresses of each treated surface layer. The research results reveal significant differences between the properties recorded in the surface integrity examination, which are based on the selected shot peening parameters. Mhaede [10] studied the effects of various process parameters of shot peening and ball-burnishing on the surface layer properties, i.e., surface roughness, microhardness and residual compressive stresses, fatigue and corrosion fatigue properties of Al-alloy AA7075 T73. The obtained results show that shot peening leads to the highest surface roughness, compared to ball-burnishing and that both treatments increase the surface layer hardness and introduced significant levels of residual compressive stresses.

James et al. [11] present useful information regarding the residual stress profiles in aluminium and steel welds, and in shot peened aluminium, obtained via synchrotron and neutron diffraction, where the effects of notches, pitting corrosion and welding joints on the aluminium alloy fatigue behaviour were investigated. Xie et al. [12] investigated the distribution of residual stresses and microstructure after shot peening. The results reveal that both compressive residual stresses and microhardness increase with the improvement of shot peening intensity in the surface deformation layers. The domain sizes are refined and the microstrain becomes severe in surface layers after shot peening. The process of shot peening was investigated in earlier studies [13] to [15], where this process, according to its energy level, can be categorised into three different cases of conventional, severe and over shot peening. They discovered that the exposed compressive residual stress on the shot peened surface of the specimens was enhanced by increasing the coverage, but this rise was not very significant. However, an increase in coverage from conventional to over played an important role in refining the grains, increasing the hardness and generating compressive residual stress. Shivpuri et al. [16] presented an elasto-plastic numerical approach to investigate effects of process parameters and surface material response on the development of subsurface residual stress. The used material was high alloy structural steel AISI4340. The results show that an increase in workpiece hardness reduces the indentation depth and consequently the magnitude of the residual stress. It has a negligible effect on the residual stress depth. Hardness increases the elastic response, including elastic recovery, and plays an important role in the development of the residual stress field. Softer materials produce deeper and larger residual stress, which is undoubtedly our aluminium alloy. Bagherifard et al. [17] investigated surface topography alterations as a function of peening parameters and processing time. They concluded that the results obtained from the numerical simulations correspond well with the roughness values measured experimentally on shot peened specimens.

Benedetti et al [18] investigated the effect of shot peening on the very-high cycle fatigue resistance of the Al-7075-T651 alloy. They carried out an extensive analysis of the residual stress field using X-ray diffraction (XRD) measuring technique. They concluded that the material removal on the surface exposes the residual stress that was present at the corresponding depth prior to polishing. Moreover, tribofinishing caused some stress redistribution in the subsuperficial peak, while the depth of the surface layer interested by compressive residual stresses remained nearly unaffected.

The objective of this study is to establish the favourable parameters of the shot peening treatment of the aluminium alloy after quenching and then preparing the alloy for artificial ageing with regard to residual stress profiles, which were measured and compared by two different methods.

This research is organised as follows. In Section 1, the experimental procedure is introduced, in Section 2, the experimental results with a discussion are presented and in Section 3, the conclusions are given.

1 EXPERIMENTAL PROCEDURE

1.1 Material Preparation

The alloy chosen for this investigation was AA-7075, which is widely used in aerospace applications due to its high strength and lightweight. It was supplied as a 10-mm rolled thick plate, from which the specimens were prepared, i.e., cutting in the longitudinal (L) and long transverse (LT) directions from the plate dimensions. The dimensions of the specimen used for blind-hole drilling were 40 mm × 40 mm. Cutting was performed with a machine cutter for the preparation of specimens for metallographic examination. The specimens were cut carefully to avoid overheating the surface, the resulting undesirable microstructural changes and the introduction of additional residual stresses into the surface. The measuring points for both methods are presented in Fig. 1.

All specimens were then ultrasonically cleaned in ethanol and rinsed with deionised water, and then dried in flowing cool air. The chemical composition of the aluminium alloy is presented in Table 1.

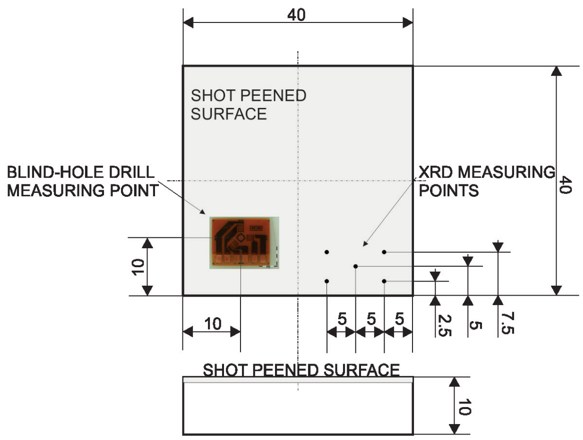

Fig. 1. *Measuring points for blind-hole drilling and XRD measurements*

Table 1. *Chemical composition of AA7075 [wt.%]*

Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	Al
5.70	2.36	1.58	0.19	0.17	0.12	0.05	0.03	bal.

1.2 Heat Treatment

The aluminium alloy was subjected to homogenisation annealing at 475 °C for 2 h, followed by quenching in water to room temperature.

1.3 Shot Peening

AA 7075 was treated with Almen intensities of 12A and 16A, while the degree of coverage was set to 100 % and 200 %. The Almen saturation curve is a conventional method to measure the kinetic energy transferred by a shot stream. The measurement of shot peening intensity is performed by standard test strips (Almen strip) and a gauge (Almen gauge) in the shot peening process. Shot peening is a well-known process. In the shot peening process, a stream of hard material shots is impacted on the work piece. As a result, a thin layer of compressive residual stress is produced close to the surface of the work piece due to the plastic deformation and work hardening of the impacted site.

The shot peening treatment has positive effects on the material surface, causing the occurrence of compressive residual stresses that increase the fatigue strength of the material and prevent the initiation of cracks and the propagation of the already existing micro-cracks [19]. Therefore, the effects of individual treatment parameters need to be known, such as the selection of a treatment medium, particle kinetic energy and the coverage of traces of individual spheres.

The Metal Improvement Company (MIC) in Austria performed the shot pening treatment using heat-treated steel spheres S170 with a diameter of 430 mm and a hardness of 420 HV_1 to 448 HV_1. The fine homogenised martensitic microstructure of the steel spheres increases the toughness of the material and has considerable resistance to fatigue strength. The chemical composition of the used spheres is presented in Table 2.

Table 2. *Chemical composition of S170 [wt.%]*

C	S	P	Fe
0.85 to 1.2	max 0.04	max 0.04	bal.

2 RESULTS AND DISCUSSION

2.1 Surface Roughness

The surface roughness was determined for the specimen in the as-received condition after heat treatment and after the surfaces were treated with the shot peening process. The surface roughness was measured in various directions.

The surface roughness describes a shot peened surface as a flat surface. The characteristics of the shot-peened specimens chosen for roughness evaluation are the mean arithmetic roughness Ra and mean roughness depth Rz. The arithmetic mean roughness Ra of the surface profile was chosen as the property used to estimate the roughness of the shot peened specimens. In studies [7] and [9], the authors generally focus only on this property when describing the surface profile. The values of Ra were determined based on the captured surface profile utilising a Taylor Hobson Surtronic 3+ profile meter and TalyProfile Lite 3.1.4 software. The profiles of the shot peened specimen surfaces were captured at a length of L = 8 mm, with ten repetitions, and recorded at different reference points.

Fig. 2 shows diagrams representing the surface roughness Ra before and after shot peening. The surface roughness increases by a factor of 10 to 20 after the shot peening process on the aluminium alloy.

The specimens treated with a higher Almen intensity show increasing surface roughness at a constant mass flow. The results reveal that the roughness increased with increasing Almen intensity, but when it comes to different coverages, i.e., from

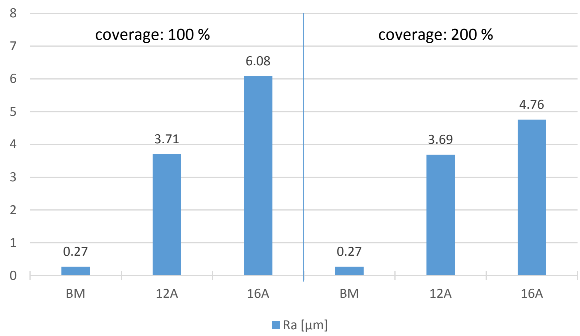

Fig. 2. *Surface roughness of base material (BM) and roughness after shot peening for aluminium alloy AA7075*

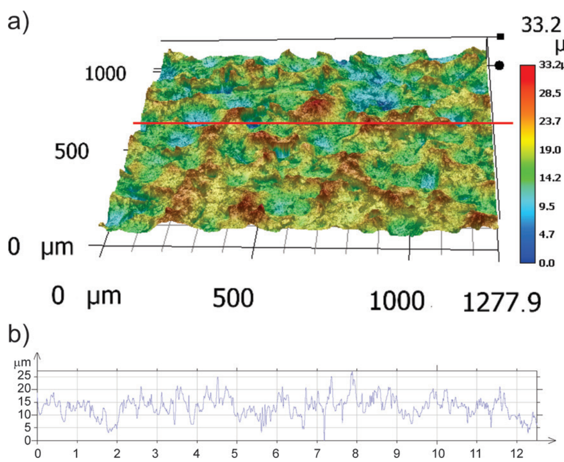

Fig. 3. *Surface roughness after SP treatment with intensity set to 12A for 100 % coverage; a) captured area roughness, b) selected profile roughness*

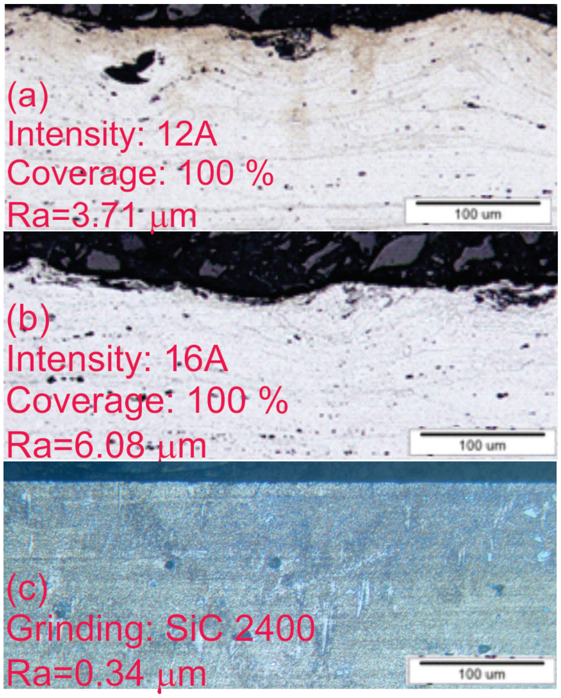

Fig. 4. *Surface roughness at 100 % coverage after SP treatment with Almen intensity; a) 12A, b) 16A and c) after grinding captured at M = 200 : 1*

100 % to 200 %, the surface roughness decreases. The decrease in the roughness can be attributed to the fact that the hardened spheres at the 200 % coverage impact several times on the same place, which flattened the surface [7].

Fig. 3 displays a sample measurement of roughness of the treated aluminium alloy after shot peening. At a coverage of 100 % and an Almen intensity of 12A, it can be seen that the total roughness profile on selected lines rises to 27.4 mm.

Figs. 4a and b presents the microstructure of the surface layer of the aluminium alloy peened with Almen intensities of 12A and 16A, while 4c represent a surface after grinding. From the figures, we can conclude that the higher Almen intensity results in higher values of Ra with deeper plastification of the material.

After grinding (silicon carbide grinding paper, grit 2400) of 100 mm, the surface roughness is in all cases of measurements almost the same, i.e., from 0.31 mm to 0.35 mm.

2.2 Microhardness Profile and Residual Stresses

Microhardness was measured with the Vickers hardness test method. The material was subjected to a load of 200 g ($HV_{0.2}$). Fifteen measurements were performed on each individual specimen, providing a reliable microhardness variation in the treated surface layer.

The first method for measuring residual stresses was a semi-destructive method. The residual stress measurement of the treated samples was implemented by an incremental blind-hole drilling method in accordance with ASTM standard [20] with an increment of 0.1 mm to a final depth of 1.6 mm. The measurements were performed to obtain the trend of residual stresses using an ultra-high-speed drilling technique [21], a tungsten carbide inverted cone drill with a nominal diameter of 1.6 mm and a micro-measurement strain recorder. For the strain measurements, the CEA-06-062-UM strain gauge rosettes were mounted on the surface of each specimen. The residual stress profiles have a strong influence on the behaviour of parts under dynamic loads. For the calculation of residual stress variation, an integral method and the H-drill program package were used. The integral method is recommended for recording and measuring rapidly varying residual stresses, in which the stress-to-noise ratio is the most prominent. Therefore, it is the method of choice in shot peening treatments [22]. The spatial resolution of the method is the highest of all the methods and it enables a separate evaluation of residual stresses for each increment of depth.

The second method for measuring residual stresses was a non-destructive XRD method. The device that has made the designs of the Proto iXRD unique is the patented Proto Position Sensitive Scintillation Detector. The XRD stress measurement technique measures only near surface stresses. The mean depth of penetration of the chromium K-alpha (Kα) X-ray beam into a steel surface is of the order of ~0.013 mm.

The XRD measurements of residual stresses were made on the same specimens, where the area was set to 20 mm × 15 mm. There were five measurements on each specimen surface and the incremental removal of the material was 0.05 mm in depth. The removal of material was made by a grinding method with a low force of 100 N and a time of 120 s. The paper used was silicon carbide grinding paper, grit 2400 from Struers.

The microhardness of the tested aluminium alloy in the initial state was 155 $HV_{0.2}$. In Figs. 5a and 6a, the results of the shot peening treatment show that the material microhardness increased in all shot peened treated specimens and that microhardness changes are dependent on the work hardening conditions. In all measurements, the highest material microhardness was obtained at a depth of 50 mm, due to the plastic deformation of the hardened layer, since after shot peening the upper layer slightly softens. The first impression of microhardness was always made very close to the top of the shot peened layer. Other studies [8], [10] and [16] also obtained and confirmed similar results regarding the microhardness after shot peening treatment.

At shot peening conditions with an intensity of 12A, the highest surface microhardness was achieved after a 200 % coverage, i.e., ~210 $HV_{0.2}$ at a depth of 50 mm. In comparison with an Almen intensity of 16A, where a peak was obtained at the same depth with 225 $HV_{0.2}$, it can be stated that the depth of the

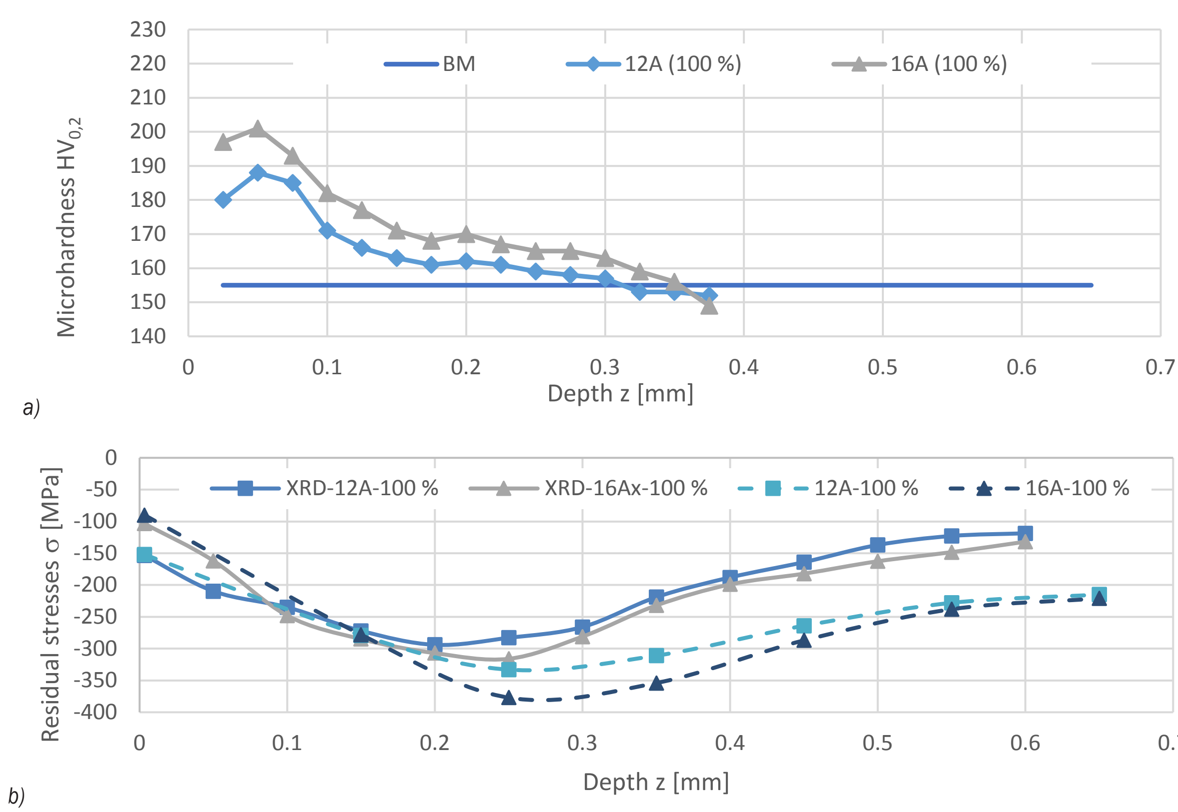

Fig. 5. *a) Microhardness measurements of treated aluminium alloy, and b) residual stresses at different Almen intensities, both for 100 % coverage*

hardened layer is independent of the selected shot peening conditions and equates to 200 mm 250 mm.

Fig. 5b illustrates the main minimal residual stresses for aluminium alloy 7075 on the subsurface layers of specimens treated with Almen intensities of 12A and 16A, with the coverage set to 100 %. Prior to shot peening, the residual stress variations were minimum due to careful mechanical preparation of the specimens, i.e., due to the cutting up, grinding and polishing of the specimen with amount around –50 MPa throughout the specimen. For blind-hole measurements, the residual stresses measured on the surface were around –150 MPa for an Almen intensity of 12A in comparison with the Almen intensity of 16A, where the amount of residual stress was smaller at –90 MPa. This can be attributed to the fact that with a greater Almen intensity, the surface of the alloy slightly softens, since the amount of displaced material is slightly larger. The softening of the surface was also confirmed by the microhardness measurements of the treated aluminium alloy. Residual stresses measured with XRD on the other side of specimens for 12A (100 %), 12A (200 %), 16A (100 %) and 16A (200 %) were –112 MPa, –114 MPa, –123 MPa and –110 MPa, respectively. Shot peened specimens with 100 % coverage show almost the same layout. The one treated with an intensity of 12A has its maximum at depth of 250 mm with a value of –295 MPa, compared with intensity 16A that reaches a maximum at the depth of 200 mm with the amount of around –315 MPa. These two curves then turn towards tensile area with the same gradient but stay in a compressive nature.

In the Fig. 6b the main minimal residual stresses for the treated aluminium alloy after shot peening with 200 % coverage and Almen intensities of 12A and 16A are presented. At this coverage, the peak is slightly shifted to greater depths, i.e., 300 mm, but the maximum amount of comprehensive residual stresses stays almost the same and rises between –340 MPa and –370 MPa for blind-hole measurements. All residual stresses have from the surface to the depth of 250 mm almost the same gradient.

Comparing with XRD measurements, the difference between intensities of 12A and 16A, where the coverage was 200 %, shows that the one treated with 16A has greater compressive residual stresses from depths of 150 mm to 600 mm with values

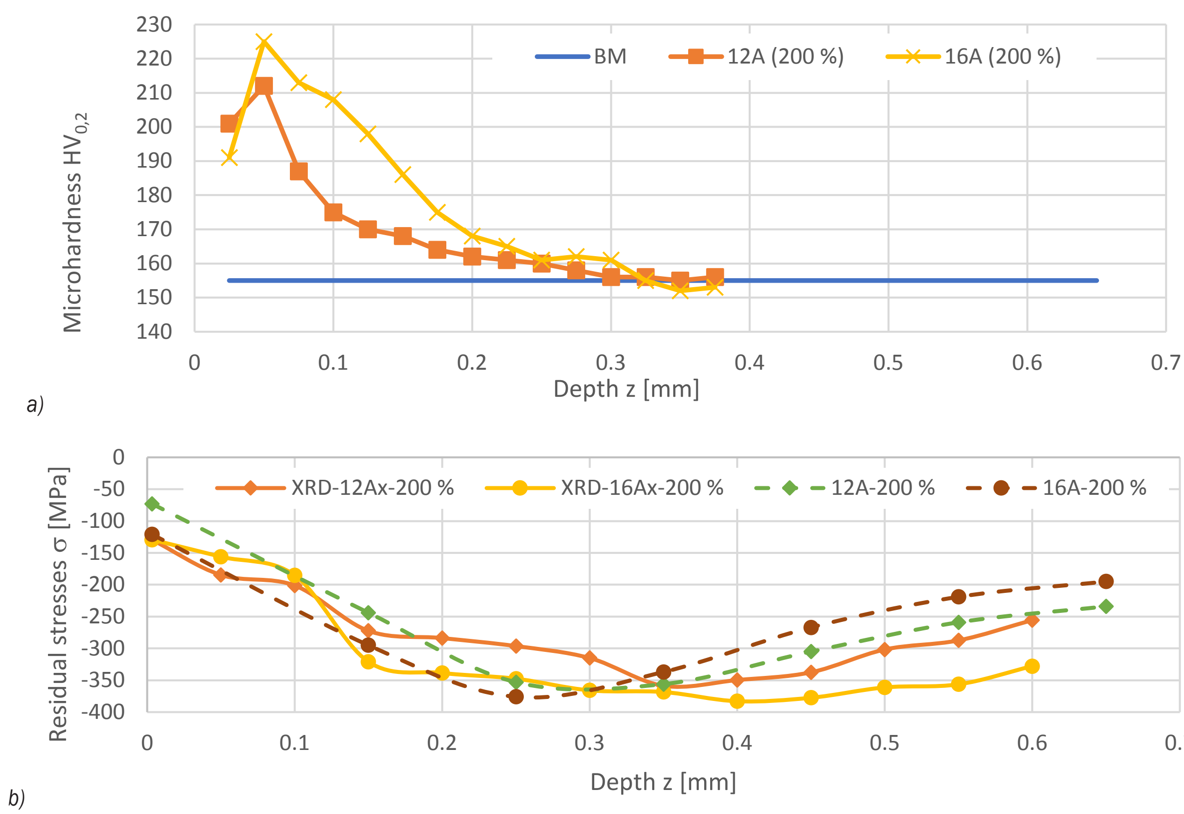

Fig. 6. *a) Microhardness measurements of treated aluminium alloy, and b) residual stresses at different Almen intensities, both for 200 % coverage*

greater than –320 MPa. At 200 % coverage and an Almen intensity of 16A, it was also found that the dislocation movement was pushed to a greater depth. The maximum obtained value of compressive residual stress was –385 MPa at 400 mm. After having reached the highest value, the residual stress profile is once again directed towards the tensile area with a small gradient and reaches –110 MPa at a depth close to 1 mm. The treated specimen with Almen intensity 12A have, on average, for 50 MPa lower residual stresses at the same depth between 250 mm and 600 mm. The value of maximum residual stress is -360 MPa at a depth of 350 mm.

The similar results with a very high effect of shot peening were presented in research by Rodopoulos et al. [23], Gallitelli et al. [24] and Marini et al. [25].

By comparing the results obtained by blind-hole drilling and XRD measurements in Figs. 5b and 6b, it can be stated that:

- At coverage, set to 100 %, there is a difference between values of residual stresses, but the depth of the obtained value of residual stress stays almost the same and is 250 mm.
- At 200 % coverage, the values of highest residual stresses are very close together, i.e. between –360 MPa and –380 MPa, but the depth varies for blind-hole drilling method and XRD method from 250 mm to 300 mm and 400 mm, respectively. At this coverage, the residual stresses stays also longer time in compressive nature. Nevertheless, differences were observed in the depth of hardening and in the value of compressive residual stresses. The increase in hardened layer may be due to the change in the microstructure of the material resulting in dislocation of grains caused by shot peening. The main difference between these two measurement techniques is that the XRD measurement is a local measurement, since the residual stresses are measured directly below the given point and the area of this point is much, much smaller than the area of the circle caused by high-speed drill. With XRD, we can make a large number of measurements, because it is also a non-destructive method while blind-hole drilling method damages the material and the measuring points cannot be so close together due to the plastification of the material.

Fig. 7 represents the extraction of all measurements made by XRD on the sample peened with Almen intensity 12A and 100 % coverage to the depth of 250 mm. From the given measurements, the scatter of XRD measurements can be seen around blind-hole drilling method results. By grinding the specimen for 100 mm a smooth surface is obtained which is good enough for all applications. At that surface, we want to know the hardness and residual stress situation. The XRD measurement method is faster than blind-hole drilling method and requires less preparation. In the surface layer of shot peened aluminium alloy, which was measured with XRD method, first the grinding increment of 0.01 mm was used to the depth of 0.05 mm. The measurements were made in five different positions and then compared with blind-hole drill method results calculated at the same depth. It was found out that the results obtained by the XRD method very well match to the blind-hole drill method results.

3 CONCLUSIONS

In this study, the effects of intensity of shot peening and coverage on residual stresses in accordance with two measuring techniques of the aluminium alloy

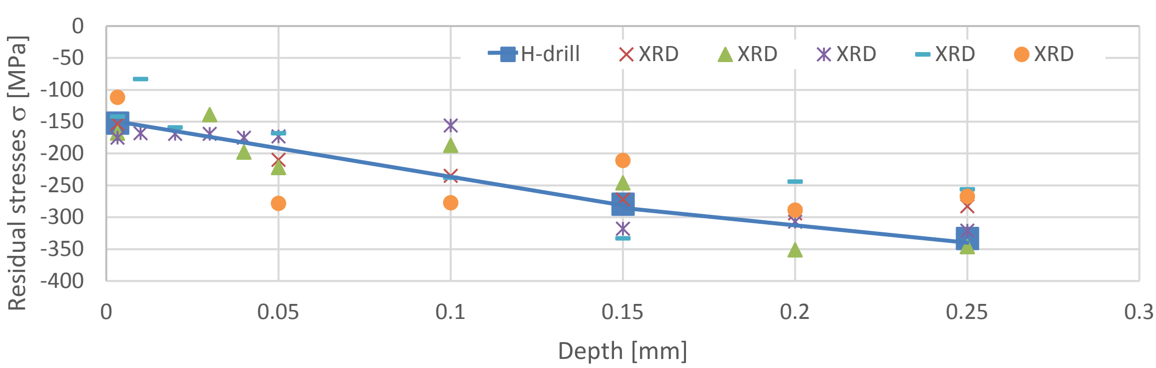

Fig. 7. *Extraction of measurement for residual stresses from XRD and comparison with H-drill*

7075 are discussed. Some important conclusions can be summarised as follows:

a) From the microhardness values can be stated that the depth of the hardened layer was between 200 mm to 250 mm and that depends on conditions of the Almen intensity.
b) After shot peening the roughness of base material increased from 0.27 mm to 6 mm. Roughness of shot peened treated aluminium alloy decreases when increasing coverage of shot peening.
c) The residual stresses in the modified layer are compressive nature at all shot peening processing parameters. The highest value of residual stress were obtained after shot peening with 16A and coverage of 200 %, i.e. –377 MPa at the depth of 250 mm.
d) From the aspect of residual stress, the measuring technique has a minimal influence on results, since the measured values of residual stresses are practically the same, regardless of coverage and Almen intensity.
e) By comparing the results between microhardness and residual stresses, it can be found that after shot peening, the microhardness is decreasing to a depth of about 0.35 mm, which coincides with the results of residual stresses. At 100 % coverage, we obtained the maximal value of residual stresses at a depth of 0.25 mm, and at 200 % coverage the depth of maximal residual stresses rises between 0.25 mm and 0.35 mm.

For practical applications we need to grind the shot peened surface for ~0.1 mm to reduce the surface roughness Ra from 6 mm to 0.35 mm. By reducing the surface roughness, we increase also corrosion resistance. We have showed that XRD and blind-hole drilling methods give accurate residual stresses results at different depths, when applying fine grinding with low forces for removing material for XRD measurement.

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