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Water and Shot Peening of Aluminum 7020

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Abstract: Water jet peening is a young technology compared to the traditional shot peening. It is a suitable method to induce compressive residual stresses in surface layers of materials with low tensile strength. The roughness is relatively low. In this study, water jet peening and shot peening is compared concerning induced compressive residual stresses and roughness at Aluminum 7020. These two parameters influence essentially the durability of a component.

Key words: Waterjet peening, shot peening, residual stresses, aluminum 7020.

1. Introduction

Peening of components to enhance durability is today a normal process. Different methods are used. Two methods are water jet and shot peening. For materials with low tensile strength like aluminum, the surface may get very rough. Therefore, the method and the parameters of peening must be well selected, and a smooth surface is obtained. In this study, the mentioned two methods with different parameters were investigated and compared.

1.1 Water Jet Peening

The technique of cutting materials using high-pressure water jets was introduced first time in 1968 by Norman Franz, a researcher at the University of Michigan USA [1]. In 1971, the first commercial water jet cutting system was developed for laminated paper tubes. In 1980, Hashish added abrasives to the water jet, and then the AWJ (abrasive water jet) was invented for the first time [2].

WJP (water jet technology) is a surface treatment technology that was introduced in the 1980s. Salko [3] uses a high-energy jet of water to strike the surface of metallic components and create plastic deformation below the recrystallization temperature that induces compressive RS (residual stress) to improve the fatigue life of components. The cavitation water jet peening was also introduced in 1987 by Blickwedel et al. [4].

After the introduction of this process, many empirical studies were carried out to determine the optimal parameters of the process and their effects on the surface structure and the fatigue of materials. Mochizuki et al. [5] studied the cavitation water jet process intending to optimize this process to improve the compressive residual stresses on the surfaces of various parts in nuclear power plants as a preventive maintenance technique. They tried to avoid the cracks due to the stresses and failures caused by fatigue [5]. Tönshoff et al. [6] examined some of the water jet variables experimentally. It has been observed that both the water jet peening process and the shot peening process can extend the service life of metals.

In 2000, Ramulu et al. [7] examined the surfaces with two different water jet methods (without and with abrasive materials). Kunaporn [8] introduced the new semi-empirical pressure distribution using the Daniewicz pressure distribution and impact pressure. This model was based on liquids that had a better correlation with the experimental results. In addition,

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the variables of the spacing and the nozzle feed rate were examined by Kunaporn [8]. Arola et al. [9] investigated the peening effects of abrasive material on service life. He explained that increasing the peening time and power supply pressure, if the surface of the part is not damaged, can create more residual compressive stresses and extend its lifetime. The beneficial influence of the peening of pure water and cavitation water on the extension of the fatigue life was also examined by other researchers [10, 11]. Grinspan and Gnanamoothy [12] treated the aluminum alloys 6063-T6 and 6061-T4 with oil cavitation jets for the first time. They found that the magnitude of the induced surface compressive residual stress in both materials decreases with increasing distance, possibly because the impact pressure decreases with increasing distance [12].

Mahmoudi et al. [13] compare the water jet and shot peening process. They used Kunaporn's semi-empirical pressure distribution to simulate the water jet process. Muruganandhan et al. [14] experimentally investigated the effects of various beam variables and their optimization on hardness, roughness and residual stresses. Ijiri et al. [15] investigated the influence of the water jet process on a combined mode with ultrasonic waves. Srivastava et al. [16] investigated the residual stress fluctuations on the welding surface after the ultrasonic peening process with a water jet.

Because of its numerous advantages over other peening methods, water jet peening has recently attracted even more attention, and experimental or numerical studies have been carried out to optimize its variables and better understand its nature [17-19]. (The results of the water jet peening are shown here based on the investigation reported in [18].)

1.2 Shot Peening

Shot peening defined in ASTM 8851 [20], is a "process for cold surface treatment by bombarding the product with a ball of solid and spherical nature that is driven at a relatively high speed", in that near-surface plastic deformations lead to internal compressive stresses and work hardening. Today also warm peening is performed [21, 22]. Shot peening is often used as a mechanical surface treatment method in the automotive and aerospace industries [23, 24]. Peening balls, which are usually made of hard materials such as steel, ceramic, or glass balls, hit a metal surface at high speed. After the impact, the elastically stressed area tends to recover into the completely unloaded state, while the plastically deformed area exhibits permanent deformation. Due to these inhomogeneous elastoplastic deformations, a compressive residual stress area is created [25, 26].

Sandblasting as an example of cleaning castings can be seen as the predecessor of shot peening. The literature on this comes from the 19th century [27]. Shot peening was introduced by Zimmerli [28, 29] and Almen [30, 31] in their respective Associated Spring Company and General Motors before 1930. In 1934, patents were granted for the shot peening machines [32]. In the years 1935 to 1945, Almen [33, 34] carried out the basic work, for example, the development of the "Almen" strip to measure the intensity.

In 1946, the measurement of the compressive residual stress of peened torsion springs was described for the first time [35]. The SAE (Society for Automotive Engineers) published its manual on shot peening in 1952 [36].

In this process, shots are accelerated to the required speed with a pneumatic or mechanical force. Pneumatic acceleration is usually achieved with highspeed air as a medium or alternatively with water (liquid). The mechanical force acceleration is usually achieved with a rotating wheel with shovels. The Almen strip test can indirectly prove that the required speed has been reached [37].

E.g. Meguid et al. [38] investigated the influence of shot speed, size, and shape on the equivalent stress and equivalent plastic strain. Numerical models have been developed in recent years with a random impingement of shots to achieve full coverage on the surface. Miao et al. [39] simulate the shot peening process on the aluminum target plate by considering vertical and angled random impacts. Mahmoudi et al. [40] investigated the effect of the initial residual stresses on the peened samples. Their study found a good agreement between numerical and experimental results [40]. Wang et al. [41] introduced a new method to investigate the relationship between the shot velocity and the air pressure. They introduce a new method to calculate the number of shots used in the combined DEM (discrete element model) and FEM (finite element model), by considering the mass flow, nozzle movement speed, nozzle-workpiece distance, and other parameters [41].

2. Experimental Procedures

The material used in these studies was aluminum 7020-T6 (AlZn4.5Mg1-3.4335). The mechanical properties of Al 7020-T6 are shown in Table 1.

2.1 Water Jet Peening

Residual stresses were created by a water jet device that had two different types of outlets with different angles. For each outlet type, different parameters were tested. Table 2 shows the water jet peening parameters in each case. Fig. 1 shows the sample during the water jet peening process.

The pressure in this table is the source pressure of the water jet device and the SOD (stand of distance) is the distance between the outlet and the sample, and the speed is the vertical displacement speed of the water jet. The ICHD (incremental center hole drilling) technique was used to measure residual stresses on the peened samples with the water jet technique.

2.2 Shot Peening

In this study, the residual stresses were generated by shot peening for two different parameter situations. These parameters are listed in Table 3.

XRD (X-ray diffraction) was used to determine residual stresses on the peened samples. The determination was done with the help of the cos-α-method [42, 43]. The equipment was a pulstec μ-X360s. The measuring spot had 4 mm diameter (Two different techniques were used because the investigations were done at two different laboratories).

Table 1 Mechanical properties of aluminum 7020-T6.

Poisson's ratio	0.34
Young's modulus	70 MPa
Density	2780 kg/m^3
Yield stress	280 MPa
Tensile strength	350 MPa

Table 2 Parameters of water jet peening.

No.	Pressure (MPa)	Stand of distance (mm)	Speed (mm/s)	Outlet angle (°)
1	100	100	100	0
2	100	80	50	0
3	150	120	100	0
4	100	80	60	20
5	150	80	120	20
6	200	80	80	20
7	200	90	40	20
8	200	90	80	20

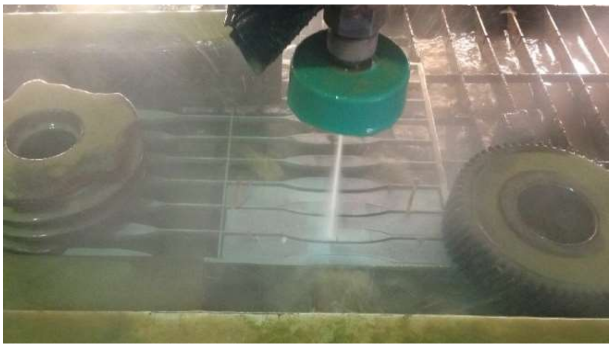

Fig. 1 Water jet peening process.

Table 3 Parameters of shot peening.

No.	Air pressure (MPa)	Mass flow (g/min)	Almen N (mm·N)	SOD (mm)	Nozzle displacement speed (mm/s)	Shot media type
1	1.5×10^5	2,000	0.19	150	35	Peenox CS; 700 HV; Ø 0.2 mm
2	2.5×10^5	2,000	0.2	150	20	Peenox Perform Plus; 700 HV; Ø 0.4 mm

Fig. 2 Sample surface after shot peening.

The shot velocity was determined using a semi-experimental formula introduced by Klemenz et al. [44 and references there] which is described below in Eq. (1).

$$V = \frac{163.5 \times P}{1.53 \times M + 10 \times P} + \frac{295 \times P}{0.598 \times d + 10 \times P} + 48.3 \times P \quad (1)$$

where V, P, M and d represent the velocity of the shot ball (m/s), the air pressure (MPa), the mass flow (kg/min), and the diameter of the ball (mm). Based on Eq. (1), the speed of the shot balls is 40 m/s in the first case and 46 m/s in the second case. Fig. 2 shows the sample surface after shot peening.

3. Results and Discussion

In this section, the results of the residual stresses generated by water jet peening and shot peening are presented and compared. In addition, after both processes, the surface roughness is compared. Moreover, stand-off distance, supply pressure, and nozzle feed rate were reported as SOD, pressure, and speed, respectively.

3.1 Residual Stress

As mentioned in the last section, the residual stresses induced by water jets are measured by the ICHD method, and the residual stresses generated by shot peening are measured by the XRD method. The results of the residual stresses caused by water jet peening for two types of outlets with angles of 0° and 20° are shown in Fig. 3. It can be seen that a smaller amount of compressive residual stress is generated with an outlet of 0° compared to an outlet of 20°. According to both figures, depth and the maximum compressive residual stress increase by increasing the supply pressure. The maximum of the compressive residual stress is at the surface that is typical for water jet peening. If the outlet is 20°, a better distribution is achieved because the reflected water jet does not affect the initial jet. Between 100 μm and 200 μm, the zero crossing of the residual stress is observed [18]. The profile has a typical shape caused by superficial shear stress [45, 46].

The result of the residual stress measurement of the shot-peened samples is shown in Fig. 4. Case 1 relates to sample 1 in shot peening in Table 3 and case 2 to sample 2 in this table. Both curves (Fig. 4) give the typical function course of Hertzian pressure [45, 46]. Increasing the velocity and diameter of the shots increases the maximum and depth of residual stresses. According to Eq. (1), air pressure is another parameter that affects the depth and maximum residual stress. As the air pressure increases, the velocity of the shots increases as well.

Comparing Figs. 3 and 4, it can be concluded that the maximum residual stresses generated by shot peening are much higher than the maximum residual stresses generated by water jet peening because the impact is higher. The plateau of the compressive residual stress in case 2 indicates that the possible maximum compressive residual stress is induced which is about 2/3 of the tensile strength, because of starting microplastification.

3.2 Surface Roughness

Roughness is a term coming from surface physics that describes the unevenness of the surface height. There are different calculation methods for the quantitative characterization of the roughness. Each of them takes different characteristics of the surface into account. The surface roughness can be influenced, among other procedures, by polishing, roller burnishing, grinding, lapping, honing, pickling, sandblasting, bristle blasting, etching, steaming, or corrosion. In this study, the surface roughness parameters of all treated samples were calculated based on the definition of ISO 4278 [47]. Here the arithmetic-mean height (R_a) was used that is expressed as in the following formular (2):

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i| \quad (2)$$

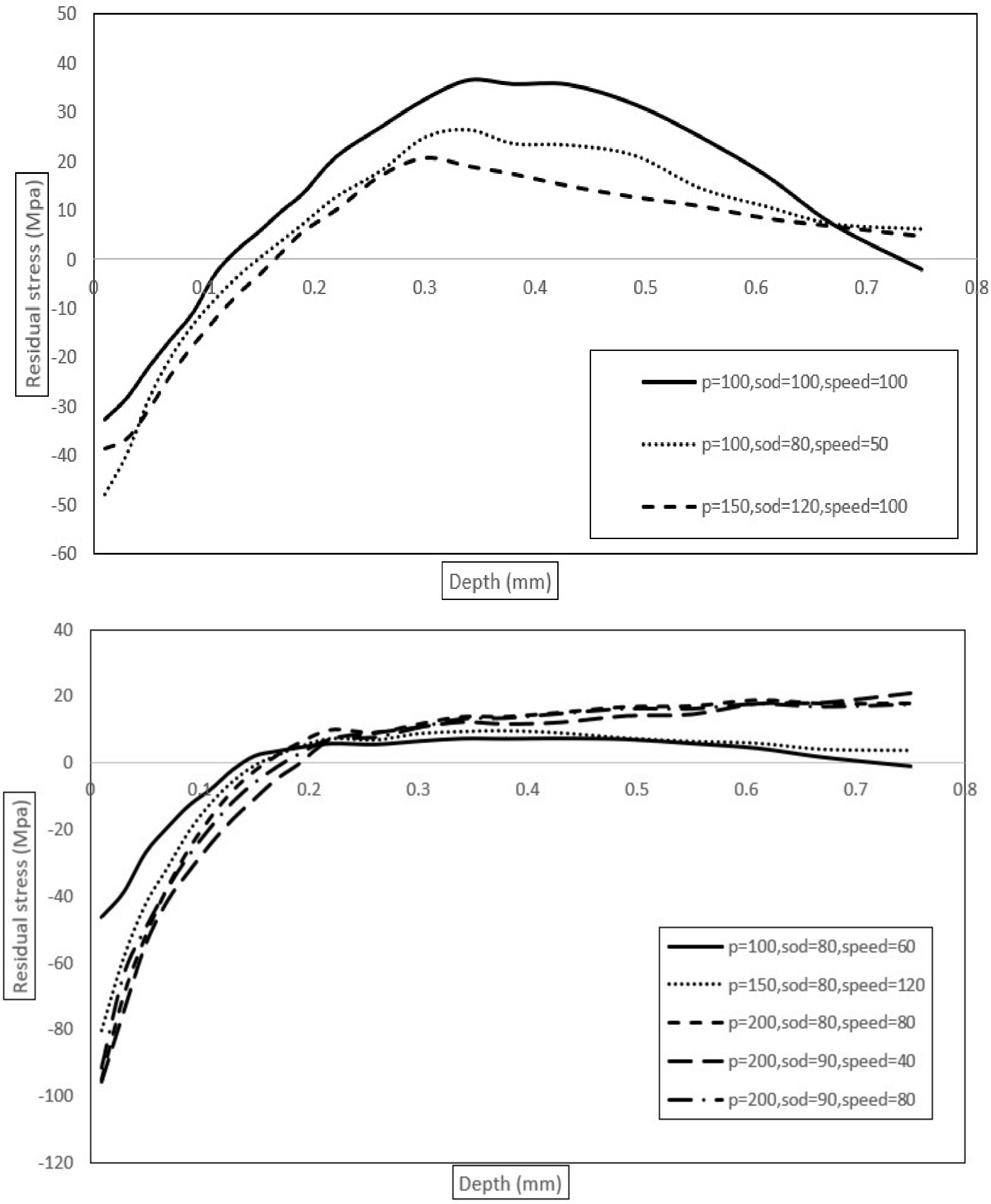

Fig. 3 Residual stresses from experimental measurements caused by water jet peening with 0° outlet (upper figure) and (lower figure) 20° outlet.

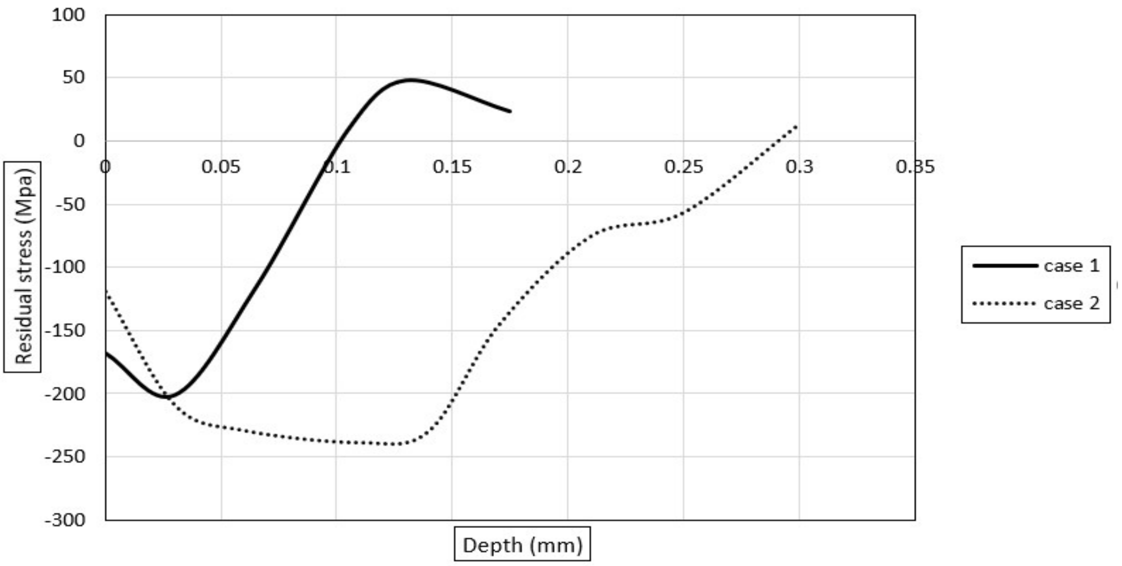

Fig. 4 Residual stresses from experimental measurements caused by shot peening

Table 4 Roughness test result.

Process		Nozzle outlet angle (°)	R_a (μm)
Water jet	*P* = 200 MPa, SOD = 90 mm, speed 60 mm/s	20	6.817
water jet	*P* = 150 MPa, SOD = 80 mm, speed 120 mm/s	20	4.931
Water jet	*P* = 100 MPa, SOD = 100 mm, speed 100 mm/s	0	3.489
Water jet	*P* = 150 MPa, SOD = 120 mm, speed 100 mm/s	0	3.787
Shot peening	case1: $P = 1.5\times10^5$ MPa	15	1.459
Shot peening	case 2: $P = 2.5\times10^5$ MPa	15	3.853

The achieved roughness parameters after the water jet peening and the shot peening are shown in Table 4. It is clear that the water jet roughness and the shot-peened roughness increase by increasing the supply pressure or the velocity of shots. If the nozzle outlet angle is 20°, the roughness is significantly higher compared with 0°. According to Table 4, the roughness of water jet peening is higher than shot peening in most of the cases that were not expected this way. A higher tangential pressure could be the reason for this result.

4. Conclusion

In this study, the effects of water jet peening and shot peening on residual stresses and surface roughness of aluminum alloy 7020 samples were experimentally investigated. The most important obtained results are as follows:

- Compressive residual stresses can be generated by water jets. However, the compressive residual stresses of water jet peening are often lower than the compressive residual stresses induced by conventional shot peening.
- Two different mechanisms (Hertzian pressure and surface plastification) cause different residual stresses profiles
- The depth of residual compressive stresses can be increased if the parameters of the water jet such as velocity, supply pressure and SOD were changed. On the other hand, the parameter of the water jet must be selected very carefully. For example, if the selected supply pressure is too low, under this pressure peening treatment cannot be carried out and performed and no compressive residual stresses are generated in the workpiece.
- Analysis of the results from different outlet angles for water jet peening indicates that it is best to use (in this investigation) the outlet with 20° for pressure above 150 MPa.

- Compared to the water jet peening process, shot peening can generate higher compressive residual stresses in the specimens with nearly the same roughness.

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