Measurement of shot velocity using particle image velocimetry and numerical analysis of residual stress at two shot peening conditions

Takahiro OHTA* and Ninshu MA**

* Department of Prime Mover Engineering, School of Engineering, Tokai University, 4-1-1 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan
E-mail: takahiro_ohta@tsc.u-tokai.ac.jp
** Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaragi, Osaka 567-0047, Japan

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Abstract
Shot peening is applied to many manufactured parts to improve the fatigue strength of metals by introducing compressive residual stress near the surface. The distribution of compressive residual stress is mainly determined by shot diameter, shot velocity, angle of incidence, and peening time which affects coverage. In this study, the shot velocity was measured using particle image velocimetry (PIV) for shots fired at two different air pressures. The finite element method was used to analyze the residual stress distribution in a high strength aluminum alloy (A7075-T6) plate during shot peening. The shot was accelerated up to a standoff distance of approximately 200 mm from the nozzle outlet. The measured maximum shot velocity increased proportionally to the air pressure to the 0.59th power. The analyzed residual stress distributions using measured shot velocity with PIV through the thickness of the specimen agreed well with the measurements under two types of peening conditions with differing air pressure and angle of incidence. The shot velocity measurement technology and the numerical model for analysis of the shot peening residual stress were both validated in this study.

Keywords: Shot peening, Particle image velocimetry, Shot velocity, Residual stress, Finite element method

1. Introduction

Shot peening can significantly improve the fatigue strength of metals, which has encouraged its widespread use in aircraft construction. Therefore, it has been of great interest to the automobile industry. Compressive residual stress and work hardening near the surface achieved using shot peening are the main reasons for the observed improvement in fatigue strength. The distribution of compressive residual stress is mainly determined by shot material, shot diameter, shot velocity, angle of incidence, and peening time (which affects coverage). Coverage is defined as the ratio of the indentation area to the material surface area. The development of computers and computing technology has enabled the finite element method (FEM) to analyze the mechanism involved in the formation of compressive residual stress through impact by multiple shots under various peening conditions.

A dynamic explicit FEM is widely employed to predict the residual stress produced by multiple shot peening. Meguid et al. (2002) analyzed the residual stress distribution in multiple shot collisions, taking into consideration the strain rate dependency of the material. Majzoobi et al. (2005) showed that the residual stress distribution formed by the collision of multiple shots is influenced by both the shot velocity and the number of shots. Miao et al. (2009) discussed the influence on residual stress distribution using a model in which shot velocity, angle of incidence, and collision position were randomly set. Hong et al. (2008) investigated the relation between peening conditions and residual stress distribution using numerical analysis, taking into consideration the interference effects of rebounding shots in multiple shot collision models. Kim et al. (2010) showed agreement between the experimental and numerical analyses of
As the shot velocity has a significant influence on the residual stress distribution, its effect was investigated using both measurement and numerical analyses. Gariépy et al. (2017) estimated the distribution of shot velocity using the distribution of the size of the resultant indentations and performing numerical analysis on the residual stress. Nordin and Alfredsson (2016) used the indentation size to estimate the shot velocity and showed that the estimated shot velocity agreed with the measured values for small diameter shots. Guechichi et al. (2013) clarified the relation between the peening strength measured using an Almen strip and the shot velocity for shot with an identical diameter and shot material. Green et al. (1981) measured the relation between air pressure and shot velocity using a velocity measurement system comprising two electrodynamic electrodes. Clausen and Stangeberg (2002) measured the relation between air pressure and shot velocity using the two-disk method. Linnemann et al. (1996) used two photovoltaic barriers to measure shot velocity and detailed the relation between air pressure and shot velocity. Barker et al. (2005) measured the relationship between air pressure and shot velocity using two electro-optical sensors. The shot velocity at a certain distance from the nozzle was measured or estimated by using the above-mentioned methods.

In some studies, the change in shot velocity after projection from the nozzle was investigated. Ogawa et al. (1994) measured the shot velocity using a high-speed shutter TV camera and detailed a calculation method for the change in shot velocity after projection from the nozzle. They also detailed formulas for the relation between shot diameter, air pressure, shot material, and shot velocity. Kirk, (2007, 2013) calculated the change in shot velocity after projection from a nozzle. Nanbu et al. (2010) calculated the change in shot velocity for fine particle shot peening after projection from a nozzle. They compared the shot velocities measured using a high-speed shutter TV camera with the calculated values. The calculated results by Ogawa et al. (1994), Kirk (2013), and Nanbu et al. (2010) were identical. They revealed that the shot continued to be accelerated by air expelled from the nozzle outlet after the shot left the nozzle, reaching its maximum velocity at a distant position from the nozzle. After the shot reached that point, the shot velocity decreased only slightly. Kubler et al. (2017) proposed a new method for measuring shot velocity using digital image correlation. This method could show the shot velocity distribution after projection from the nozzle. However, the relation between the shot velocity and the residual stress distribution based on direct measurements was not investigated in any of the aforementioned studies.

To the best of our knowledge, there has been no study conducted that directly shows the relation between measured shot velocity, angle of incidence, and measured residual stress distribution. The shot velocity distribution can be clarified within a wide range by applying particle image velocimetry (PIV) and using high-speed video cameras developed in recent years. In this study, the shot velocity was measured using PIV. The residual stress distribution that was analyzed with FEM and compared with the measured residual stress distribution in a high-strength aluminum alloy (A7075-T6) exposed to shot peening. The effects of shot velocity and the angle of incidence on the residual stress distribution were clarified.

2. Shot peening experimental device and conditions

A direct-pressure-type shot blast device PNEUMA-BLASTER (Fuji Manufacturing Co., Ltd. P-F0-4AICM-501) was used in the experiment as shown in Fig. 1. The shots were made of low-alloy steel that included manganese and silicon with a hardness of 45 to 52 HRC. The shot diameter was 0.4 – 0.7 mm (ASR-170: AMS2431/1D - Aerospace Material Specifications). The experiment was performed under two different conditions as shown in Table 1. The peening time was set to 160 s with a coverage of 100% or more, and the standoff distance was 400 mm. The angle of incidence \( \theta \) was set at 90° in Test-1 and 45° in Test-2. The 90° angle involved a vertical collision of shots onto the specimen. The minimum air pressure in this shot blast device was 0.14 MPa. The peening intensity of Test-1 was 0.25 – 0.28 mm A, and the peening intensity of Test-2 was 0.16 – 0.18 mm A. The peening intensity was measured with the arc height of A-type Almen strip. The peening intensity was 0.22 – 0.25 mm A when the air pressure was 0.14 MPa and \( \theta \) was 90°, which was slightly different from that at 0.2 MPa. Therefore, \( \theta \) was set to 45° in Test-2. The specimen was a high strength aluminum alloy (A7075-T6) with a hardness of 170 HV, and its dimensions were 60 mm in width, 75 mm in length, and 7 mm in thickness.

The shot velocity was calculated by recording the flight of the shot with a high-speed camera and using PIV. The high-speed camera was a Fastcam Mini AX200 made by the Photron Co., Ltd. The shutter speed was 1/50,000 s, and the frame speed was 5000 fps. The resolution was 1024×1024 pixels, and an area approximately 200 mm from the
nozzle was recorded. PIV was applied via the flow measurement system (FrTSPIV) from Flowtech Research Co., Ltd. The measurement frequency was 5000 Hz, and the average velocity over a period of 0.04 s was obtained. The direct cross correlation method was used to estimate the amount of movement. The interrogation window was enlarged to 200 mm × 26 mm owing to the large particle movement. As a result, the shot velocity could not be calculated at the edge of the image.

The residual stress was measured using an X-ray diffraction method and measuring device μ-X360 (Pulstec Co., Ltd.) based on the cos α method. The X-ray diameter used in this residual stress measurement was approximately 2 mm, which has been successfully used to accurately measure surface stress, as reported by Lin et al. (2017). To obtain the residual stress distribution through the thickness, the surface was gradually electropolished, and the residual stress was repeatedly measured at increasing depths.

![Fig. 1 Shot peening experimental device.](image)

Table 1 Experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>Test-1</th>
<th>Test-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot Diameter</td>
<td>ASR-170 (Average Dia.: 0.5 mm)</td>
<td>ASR-170 (Average Dia.: 0.5 mm)</td>
</tr>
<tr>
<td>Air pressure [MPa]</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>Peening time [s]</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Standoff distance [mm]</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Angle of incidence θ</td>
<td>90°</td>
<td>45°</td>
</tr>
</tbody>
</table>

3. Experimental results

3.1 Measured shot velocity

The distribution of moving shots observed with the high-speed camera is shown in Fig. 2. No specimen was set in this particular event. In both Test-1 and Test-2, the projected shots flew in a straight line for a distance of 40 mm from the nozzle. They demonstrated slight spreading beyond 40 mm. Shots rebounding off the walls were flying at low velocities both above and below the main flow.

![Fig. 3 Vector diagram of the shot velocity.](image)

A vector diagram of the shot velocity is shown in Fig. 3, and Fig. 4 shows the change in velocity of the three lines near the center line of the shot flow. The distance between each line was approximately 3.3 mm. The slight variation in the velocity seen in Test-1 is presumed to be caused by fluctuation in the number of projected shots. In both Test-1 and Test-2, after the shots were projected from the nozzle, their velocities increased up to approximately 200 mm from the nozzle.

The maximum velocity was 39.5 m/s in Test-1 and 32.1 m/s in Test-2. The air pressure used in Test-1 was 1.42 times greater than that used in Test-2, and the shot velocity of Test-1 was 1.23 times greater than the shot velocity of Test-2. The shot velocity thus increased in proportion to the air pressure to the 0.59th power. Ogawa et al. (1994) reported that the shot velocity was proportional to the air pressure to the 0.57th power in the case of direct-pressure-type shot peening. This was almost identical to the results obtained in this experimental study.

The shot velocity distributions shown in Fig. 3 and Fig. 4 were identical to the previous calculation results for changes in shot velocity. Ogawa et al. (1994), Kirk (2013) and Nanbu et al. (2010) described the shot velocity...
distribution as follows: The air had an almost uniform velocity immediately after being forced out of the nozzle. The air velocity decreased thereafter, and the air flow diffused due to shear friction with the surrounding atmosphere. The air flow in the central zone maintained a uniform velocity. The shot velocity was slower than the air velocity at the nozzle outlet. The shot was accelerated by the air flow and reached a maximum shot velocity at a particular distance from the nozzle. Subsequently, the shot velocity decreased, but the deceleration was less owing to inertia.

In our previous study using the same equipment and shots, the peening intensity hardly changed when the stand distance was between 300 mm and 400 mm at an air pressure of 0.2 MPa (Ohta and Inoue, 2018). It was estimated that the shot velocity at the standoff distance of 400 mm was almost the same as the shot velocity of 200 mm.

![Fig. 2 Images of shot projection captured by the high-speed camera. (a) Test-1, (b) Test-2](image)

![Fig. 3 Shot velocity distribution measurement results generated using PIV. (a) Test-1, (b) Test-2](image)

![Fig. 4 Shot velocity distribution measurement results generated using PIV. (a) Test-1, (b) Test-2](image)

Figure 5 shows the velocity distribution of the cross section of the shot flow at 0.2 MPa. As the position from the nozzle became farther, the shot velocity and the uniform velocity area increased. However, there was no change between 149 mm and 189 mm. At 189 mm, the velocity was approximately uniform at the center of the shot flow, and the width of uniform velocity was approximately 20 mm. Our previous study which used glass shots showed that the
impact pressure distribution of the shots was flat near the center of the shot flow (Ohta, 2017). The distributions of the shot velocity and impact pressure were similar. Figure 6 shows the relation between the air pressure and the cross-section shot velocity distribution. The shot velocity was faster when the air pressure was 0.2 MPa than that at 0.14 MPa; however, the shot velocity distributions profile at 0.2 MPa and 0.14 MPa were the same.

The advantages of using PIV are demonstrated in Fig. 3 and Fig. 4; we are able to obtain a visualization of the distribution of shot velocity after shots was projected from the nozzle and measure the quantitative change of shot velocity. Furthermore, the cross-section shot velocity distribution could be visualized. In the future, higher-precision measurement will be utilized if high-resolution high-speed cameras are applied.

![Fig. 5 Effect of position in Fig. 4 on cross-section shot velocity distribution at 0.2 MPa](image1)

![Fig. 6 Effect of air pressure on cross-section shot velocity distribution at 189 mm in Fig. 4](image2)

### 4.1 Measured residual stress

Figure 7 shows the distribution of residual stress through the thickness of the specimen near the surface. Our previous study showed that the $y$-direction stress was slightly smaller than the $x$-direction stress in the compressive residual stress near the surface in the numerical analysis; however, there was no significant difference between the $y$-direction stress and the $x$-direction stress owing to the large variation in the stress measurement in the experiment (Ohta et al., 2019). Therefore, only the $y$-direction stress was evaluated. In Test-1 with the vertical shot peening, the stress components in the $x$ and $y$ directions have isotropic characteristics. In Test-2 with the $45^\circ$ shot peening, only the $y$-direction stress component (inclination direction) was plotted. Notably, the residual stress distributions in both Test-1 and Test-2 possessed a similar pattern. The residual stress on the surface was compressive stress in both tests and its value was approximately $-200$ MPa in Test-2 and changed from $-200$ MPa to $-300$ MPa in Test-1. The maximum compressive stress was 0.1 mm under the surface and was higher in Test-1 than in Test-2. Additionally, the depth of the compressive residual stress was greater in Test-1 than that in Test-2.

With regard to the depth of compressive residual stress due to shot peening, Ohta et al. (2019) showed that it was proportional to the collision velocity ($v \times \sin \theta$) when shot diameter and material were same. $v \times \sin \theta$ represents the
vertical velocity component when the shot collides with the material. Nouguier-Lehon et al. (2013) showed that the depth of plastic strain in ultrasonic shot peening was also proportional to the perpendicular collision velocity ($v \times \sin \theta$). In Test-1, the shot velocity $v$ was approximately 39.5 m/s, and the angle of incidence $\theta$ was 90°. In Test-2, the shot velocity $v$ was approximately 32.1 m/s, and the angle of incidence $\theta$ was 45°. The perpendicular collision velocity $v \times \sin \theta$ was 22.7 m/s in Test-2, and $v \times \sin \theta$ in Test-1 was 1.72 times greater than that in Test-2. The compressive residual stress reached a depth of approximately 0.35 mm in Test-1 and approximately 0.2 mm in Test-2. The depth of compressive residual stress in Test-1 was approximately 1.75 times greater than that in Test-2. Thus, the depth of compressive residual stress was almost proportional to $v \times \sin \theta$.

4. Modeling and numerical analysis of shot peening residual stress

The residual stress distribution was analyzed by numerical analysis and compared with the experimental results. The numerical analysis of the shot peening process was conducted using dynamic explicit FEM code LS-DYNA. The FE model of Test-2 is shown in Fig. 8. First, transient stress and strain were analyzed by applying multiple shots at a given impact velocity and defining the contact between shots and the upper surface of the specimen. The base of the specimen was fixed to reduce the influence of vibration. When the shot peening process was complete, the base of the specimen was free, and residual stress could be obtained by performing stress release analysis using the static implicit method. The stress and strain occurring in the shot peening process were considered to be elasto-plastic. Mixed hardening law was used in the FE analysis. The stress-strain curve of the aluminum alloy (A7075-T6) is shown in Fig. 8.

An eight-node hexahedron element with reduction integration formulation was employed in the modeling. The size of the element was 0.03125 mm in $z$-direction near the surface and 0.0625 mm in the $x$ and $y$ directions. In the FE model, 1200 shots were randomly impacted onto the shot peening area of 3.1 mm × 3.1 mm as shown in Fig. 8, with an imparted initial velocity (the shot velocity). The shot impact locations were randomly set with an intervening gap of 0.05 mm between them. To avoid the simultaneous impact of all shots with the specimen, only one shot was allowed to impact the specimen at any one time. The shot was spherical with a diameter of 0.5 mm and was modeled with an
elastic body. The initial velocity was set at 40 m/s in Test-1 and 32 m/s in Test-2; these values were obtained from the measured results for the shot velocity. The coefficient of friction $\mu$ between the shot and the specimen was set at 0.2 considering no lubrication. The previous study showed that the coefficient of friction had a minor effect on the residual stress distribution (Ohta et al., 2019).

In Test-1, the indentation had an axisymmetric shape. The indentation diameter was approximately 0.25 mm. Additionally, when 1200 shots were projected, the coverage was approximately 610% in the case of uniform collision. In Test-2, the indentation was asymmetrical, and shear deformation occurred due to friction between the shot and the surface. The indentation was elliptical with a minor axis of 0.1875 mm and a major axis of 0.25 mm. When 1200 shots were projected, the coverage was approximately 460% in the case of uniform collision. However, the shots did not always collide uniformly over the entire surface because they were randomly placed, and the indentations could overlap. The residual stress was evaluated by taking the average of 2304 elements at a particular depth within the range of 3 mm × 3 mm at the center of the specimen.

5. Analyzed shot peening residual stress

Figure 9 shows the distribution of the $y$-direction residual stress component near the surface evaluation area (3 mm × 3 mm). Each element experienced different stress. There was a small compressive stress and a local tensile stress at the surface. However, just below the surface, there was compressive stress in all regions. Yasukawa et al. (2014) measured the stress at ultrafine regions on the surface of a peened spring steel plate using X-ray diffraction. They showed that although tensile stress also remained in a microscopic area of approximately 0.1 mm, macroscopically the residual stress at the surface was compressive stress. The analysis result for residual stress distribution at the surface agreed well with the micro-stress measured by Yasukawa et al. (2014). In this study, the residual stress was evaluated by averaging 2304 elements at the same depth.

Figure 10 shows a comparison between the analysis and experimental results of the residual stress distribution in the thickness. As shown in Fig. 9, the numerical analysis results of residual stress were different for each element. The error bars shown in Fig. 10 are three times the standard deviation of each element. The error bar in the experimental results shows the standard deviation at the time of X-ray residual stress. In Test-1 and Test-2, the analyzed results agreed with the experimental results when the variation due to error was considered. The large compressive residual stress induced by shot peening near the surface could contribute to the improvement of fatigue strength.

As described above, the analyzed residual stress and its distribution in Test-1 and Test-2 agreed well with the measured values for different angles of incidence and shot velocities when the measured shot velocity was used in the analysis. The validity of both the shot velocity measurement technology and the numerical analysis model for calculating shot peening residual stress were proved in this study.
Fig. 10 Experimental and numerical analysis results of the residual stress distributions. Error bars are three times the standard deviation of each element.
(a) Test-1, (b) Test-2

6. Conclusion

The shot velocity in shot peening was measured using a high-speed camera and PIV under two different conditions. The residual stress distribution was analyzed by numerical analysis and compared with the experimental results. The residual stress distribution was analyzed based on FE modeling and two-stage simulation process using the measured shot velocity.

1) The shot velocity measured using PIV was increased up to a standoff distance of approximately 200 mm from the nozzle outlet. The maximum velocity was 39.5 m/s at air pressure of 0.20 MPa and 32.1 m/s at 0.14 MPa for steel shots with an average diameter of 0.5 mm. The measured maximum shot velocity increased in proportion to the air pressure to the 0.59th power. Using PIV was an advantage because we were able to visualize the distribution of the shot velocity after shots was projected from the nozzle and measure the quantitative change of the shot velocity. In the future, higher-precision measurement will be utilized if high-resolution high-speed cameras are applied.

2) The analyzed residual stress and its distribution for different angles of incidence and shot velocities agreed with the measured values. The shot velocity measurement technology and the numerical model for analysis of the shot peening residual stress were both validated.

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