Cavitation Shotless Peening for Surface Modification of Alloy Tool Steel*

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Cavitation Shotless Peening (CSP) is a new method of surface modification. Cavitation impacts induced by the collapse of cavitation bubbles produce compressive residual stress and work hardens the material surface. In the case of CSP, shots are not required and therefore we call it Cavitation Shotless Peening. In CSP, cavitation is induced by a submerged high-speed water jet, i.e., a cavitating jet, for which the intensity and region of cavitation impact can be controlled by parameters such as the upstream pressure and nozzle size. The authors have already shown that the lifetime of forging die treated by CSP can be extended by about 50% compared with non-peened forging die. In this paper, in order to make clear the mechanism by which the lifetime of forging die is increased, an alloy tool steel (JIS SKD61) was tested both in peened and non-peened conditions. Compressive residual stress was measured by an X-ray diffraction method. It was evident from a comparison between the non-peened specimen and the cavitation shotless peened specimen that CSP improved the mechanical properties of the forging die thus giving it a longer lifetime.

Key Words: Surface Treatment, Residual Stress, Work Hardening

1. Introduction

Compressive residual stresses are induced in the surfaces of alloy steels using various surface enhancement methods to improve the fatigue life. Cavitation Shotless Peening (CSP) is an emerging technology for surface modification. In CSP, cavitation impacts are induced by a submerged high-speed water jet and the collapsing cavitation bubbles produce compressive residual stress and work hardens the material surface. The cavitation impacts can be controlled by parameters such as the upstream pressure and nozzle size⁽¹⁾⁻⁽³⁾. Since cavitation occurs in water, the thermal effects on the material surface are negligible. In comparison to water jet in the air, CSP has an additional advantage in that its working pressure is higher and the surface area treated on the specimen is wider^{(4),(5)}.

One of the present methods of improving the hardness of forging die is by Plasma Ion Nitriding (PIN). PIN is expensive and the process leaves a friable surface compound layer consisting of mixed ion nitrides. During the forging process the compound layer can spall, producing debris which is highly abrasive. This problem may be controlled by having a further finishing operation on the end product thereby increasing the manufacturing cost.

Forging die treated by CSP has an extended lifetime of 50% compared with non-peened forging die⁽⁶⁾. Furthermore, there is no post-machining required after CSP, thus giving a low-cost product coupled with improved fatigue strength⁽⁷⁾⁻⁽¹⁰⁾. Since there are no solid body collisions in CSP, the surface finish is superior in comparison to shot peened specimens. With respect to forging die, industries are now focused on cost-cutting operations such as lower processing times, almost zero contamination and faster treatment cycles. CSP will be a solution-provider in the forging die industry.

In the present study, in order to make clear the mechanism by which the lifetime of forging die is improved by CSP, the residual stress on alloy tool

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steel (JIS SKD61) was measured by an X-ray diffraction method. The surface roughness was measured using the surface profile meter and the hardness determined on a Vickers pyramid hardness tester. Comparison of non-peened, shot-peened and CSP specimens was done to demonstrate the effects on the mechanical properties.

2. Experimental Facilities and Procedures

Figure 1 shows the experimental set-up of the cavitating jet apparatus. The test chamber was filled with tap water and then the water jet, pressurised by a plunger pump, was passed through a nozzle having a throat diameter of 1.8 mm. The upstream and downstream pressures at the nozzle measured by the pressure transducers were 30 MPa and 0.42 MPa, respectively for the non-nitrided material. The upstream pressure for the nitrided material was 50 MPa. The specimen, a rectangular bar of 210 mm × 15 mm × 19 mm, was mounted along the motor axis to enable it to be moved laterally. The cavitating jet impinges the specimen at 90 degrees to its axis while the motor scans at a speed of 1 mm/s.

The main parameter of the cavitating jet is the cavitation number, which is defined as the measure of the resistance of the flow to cavitation^{(1),(11),(12)}. In nozzles and orifices, the flow velocity depends on the pressure difference between the upstream and downstream pressures. Hence the cavitation number σ is given by:

$$\sigma = \frac{p_2 - p_v}{p_1 - p_2} \quad (1)$$

where p_1 , p_2 , and p_v are the upstream, downstream and vapour pressures, respectively. Since $p_1 \gg p_2 \gg p_v$, Eq.(1) can be rewritten as:

$$\sigma = \frac{p_2}{p_1} \quad (2)$$

The higher the cavitation number, the less likely cavitation is to occur; the lower it is, the more likely.

Fig. 1 Cavitating jet apparatus

The standoff distance s_a , a variable of major concern, is defined as the distance between the upstream corner of the nozzle throat and the surface of the specimen under test. Hence, the optimum standoff distance s_{opt} is determined qualitatively by an erosion test in which the standoff distance is varied. In this paper, the optimum standoff distance was 60 mm. The residual stress was measured at different processing time per unit length t to determine the optimum scanning speed v_{opt} . Thus, the processing time per unit length is expressed as the ratio of the number of scans n to the scanning speed v .

$$t = \frac{n}{v} \quad (3)$$

Soyama et al.^{(13),(14)} have demonstrated the peening effects on hardened steel and aluminium alloy by comparing the arc heights of shot peened and CSP specimens using an alumen strip. With respect to this, CSP proved to be superior. The shot peening conditions were as shown in Table 1.

The coordinate system (x, y) on the material surface is as shown in Fig. 2. The normal stresses σ_x , σ_y , and shear stress τ_{xy} were calculated using the following equation:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ 2\tau_{xy} \end{Bmatrix} = \begin{bmatrix} \cos^2 \theta_a \sin^2 \theta_a \sin \theta_a \cos \theta_a \\ \cos^2 \theta_b \sin^2 \theta_b \sin \theta_b \cos \theta_b \\ \cos^2 \theta_c \sin^2 \theta_c \sin \theta_c \cos \theta_c \end{bmatrix}^{-1} \begin{Bmatrix} \sigma_a \\ \sigma_b \\ \sigma_c \end{Bmatrix} \quad (4)$$

Similarly, the two principal stresses, σ_1 and σ_2 , were obtained from σ_x , σ_y , and τ_{xy} by the expression:

$$\sigma_1, \sigma_2 = \frac{(\sigma_x + \sigma_y)}{2} \pm \frac{\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2}}{2} \quad (5)$$

The values for θ_a , θ_b , and θ_c were 0, 60 and 120 degrees, respectively. The X-ray tube, of Cr tube type and the $K\alpha$ ray, was operated at a voltage and current of 30 kV and 8 mA, respectively. The solar slit angle and the slit width were 1 degree and 4 mm, respectively. The diffraction angle 2θ and the stress factor of

Table 1 Shot peening conditions for JIS SKD61

Shot pressure (MPa)	Peening time (s)	Arc height (mmN)
0.1	5	0.323

Fig. 2 Coordinates of stress measurements

the X-ray diffraction method were 156.4 degrees and -318.0 MPa/deg., respectively^{(15),(16)}. The diffraction angle was determined by a half value of width method while the residual stress was determined by the $\sin^2\psi$ technique, having a six-point on the $2\theta-\sin^2\psi$ diagram. The primary advantage of the $\sin^2\psi$ technique is that it establishes the linearity of the lattice spacing of crystal plane as a function of $\sin^2\psi$, demonstrating that X-ray diffraction residual stress measurement is possible on the specimen.

The tested material was an alloy tool steel (JIS SKD61). All the specimens tested were first heat-treated at 873 K for 1 hour and then quenched, followed by a further heat-treatment at 1 123 K for 1 hour and 1 295 K for 1.5 hours. The materials were then tempered at 833 K for 5 hours. In order to reveal the effectiveness of introducing compressive residual stress to hot forging die, the residual stress of the specimen treated by CSP was measured after heat-treatment at 623 K for 10 hours. This post heat-treatment process was done to simulate the heat-treatment conditions of a hot forging die.

3. Experimental Results

Figure 3 shows the relationship between the residual stress on the specimen surface and processing time per unit length. Notice that the residual stress has increased with the increase in processing time. The residual stress on the surface of the specimen at time, $t=0$ was -680 MPa. This increased gradually to its saturation limit of about $-1\,400$ MPa after 40 s/mm. Longer processing times caused work hardening on the sub-surface layer. This is due to the fact that further elastic strains changes the mean lattice spacing⁽¹⁷⁾. The processing time for nitrided material was 40 s/mm (see Fig.3.), while for non-nitrided material which had similar tendency was 72 s/mm. In

Fig. 3 Residual stress vs processing time of nitrided specimen

CSP, there is an incubation period in which plastic deformation takes place without erosion. The residual stress saturates within the range of $1/25$ to $1/5$ of the incubation period⁽⁴⁾. At present condition, the width of the treated area was 40 mm.

In determining the residual stress for the case of nitrided material, the principal stresses were measured in the $x-y$ plane. The results were then plotted against the depth from the surface as shown in Fig. 4. There was a significant increase in compressive residual stress for the principal stresses, σ_1 and σ_2 . At the surface, the compressive residual stress for the non-peened specimen was 620 MPa. After CSP and post heat-treatment the compressive residual stress was 1 267 MPa. Considering the extreme positions of the residual stress measurements on the specimens, i.e. at zero and 80 μm , as a basis for comparison, the increase in residual stress value as a result of CSP was more than 32% despite the specimens' post-heat treatment of 623 K for 10 hours.

Figure 5 shows the relationship between the depth from the surface and hardness of the nitrided material. The result compares the non-peened and CSP specimens before and after heat-treatment, i.e. 623 K for 10 hours. It is demonstrated that the CSP speci-

Fig. 4 Depth from the surface vs residual stress of nitrided material

Fig. 5 Depth from the surface vs hardness of nitrided material

Fig. 6 Depth from surface vs residual stress on non-nitrided material

men subjected to a 10-hour heat-treatment had the highest hardness value of $H_v=1023$. Prior to heat-treatment, the specimen had a hardness value of $H_v=987$.

For the case of a non-nitrided specimen treated by CSP compared with non-peened and shot peened specimens, the principal stresses σ_1 and σ_2 were measured in the x - y plane in order to determine the residual stress. The results are plotted in Fig. 6.

For both σ_1 and σ_2 , all specimens displayed a general pattern of residual stress. However, low compressive residual stress values were obtained for the non-peened samples. The residual stress of the shot-peened specimen has S-shaped curves and is higher at a depth of 20 μm . This is because in shot peening, the high velocity impact of each particle of shot stretches the surface initially in tension, and leaves a dimple with a region of compression in the centre upon rebounding. Thus, the region of maximum residual stress is attained at some depth longitudinally below the centre of the arc radius of each dimple. Okada et al. also showed that shot peening produces a Hertzian stress distribution due to the solid contact of the spherical indenter. However, both at the surface and at greater depths, the specimen peened by CSP had higher residual stress. The compressive residual stress has a maximum value on the surface because the pressure distribution of cavitation impact on the surface is cone-shaped⁽¹⁸⁾. Thus, the pressure is very high at the center of the cone and lower on the outer edges. In CSP, the cavitation bubbles cause multiple continuous shots. This is comprised of large shots, which are responsible for deep impacts and high compressive residual stress, and small shots that contribute to low compressive residual stress. With reference to the non-peened condition, the CSP specimen showed a remarkable increase in residual stress of about 500 MPa in the x - y plane.

Fig. 7 Surface morphologies. (a) Non-nitrided JIS SKD61 specimen, (b) Nitrided JIS SKD61 specimen

Figures 7(a) and 7(b) show the surface morphologies of the non-peened, shot-peened and CSP specimens, respectively, for both non-nitrided and nitrided specimens. In the shot peened specimen, the surface had a continuous wavy dimple as opposed to CSP which had a smooth continuous surface with small isolated cavities. The average value for the surface roughness was lower in the CSP specimen than in the shot peened specimen illustrating that the CSP specimen had a better surface finish.

4. Conclusions

In the present study, cavitation bubble impacts induced by a submerged water jet were used to introduce compressive residual stress on an alloy tool steel (JIS SKD61). Residual stress and hardness were determined using X-ray diffraction and a hardness tester, respectively. Surface morphologies were examined using a surface profile meter and the results compared with non-peened and shot peened specimens. The key points are summarized as follows:

1. Longer processing times increase the compressive residual stress as a result of work hardening of the specimen sub-surface layer.
2. Heat-treatment may cause either an increase or reduction in residual stress. Heat-treating the specimen for 10 hours caused the stress field to flow away and by CSP, compressive residual stress was introduced into the material thereby increasing the fatigue strength.
3. Spallation effects on forging dies can be reduced by CSP thus improving the surface finish of forged components and hence a reduction in the manufacturing cost.
4. CSP can introduce compressive residual stress deeper than shot peening without increasing the surface roughness.

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