ULTRA HIGH PRESSURE WATERJET PEENING

PART I: SURFACE TEXTURE

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ABSTRACT

An experimental study was conducted to investigate the influence of high-pressure waterjet peening conditions on surface characteristics of a 7075-T6 aluminum alloy. Surface profilometry and scanning electron microscopy (SEM) were used in characterizing the surface texture and topography. Surface characteristics in terms of surface texture on peened specimens in relation to peening conditions were analyzed and discussed. It was found that the magnitude of erosion on material surface by the impingement of high-pressure waterjets was strongly dependent on the applied peening conditions.
1. INTRODUCTION

Waterjet peening is a recent surface treatment technique that has been developed to improve the fatigue performance of materials as an alternate to the conventional shot peening process [1-5]. Most of the surface processing methods not only affects the surface layers but also alters the surface microstructural irregularities. The local irregularities or the surface roughness is the stress concentrations, which reduce the fatigue limit of the material. In addition, surface roughness and tolerance are also closely related, and it is generally necessary to specify a smooth finish to maintain a fine tolerance in the finishing process. For many practical design applications, it is the tolerance and strength requirements that impose a limit on the maximum allowable roughness. The reliability of manufactured components is often critically dependent upon the quality of surface produced by machining, and the surface layer may drastically affect the strength and chemical resistance of the material.

Prior studies [6-16] have reported that the high-pressure flow of water at supply pressure below 150 MPa have the same deformation effects as conventional shot peening, but with negligible changes in surface roughness and topology. However, the common problem of using peening is the introduction of surface and subsurface damage and erosion on the target. Erosion and micro-fracture induced by the jets are expected if the applied process conditions are beyond a certain threshold values of target material. Process conditions that include pressure, traverse rate, stand off distance, jet exposure time, and the types of jets (round or fan). There is no systematic investigation is conducted to study the surface textures generated by waterjet peening process that includes the round and fan jets.

The objective of this study is to evaluate the performance of high-pressure waterjets (P ≥ 150 MPa) on a 7075-T6 aluminum alloy through an examination of surface characteristics. Surface characteristics induced by different jet conditions were evaluated and discussed to define suitable peening conditions. Surface characteristics of the component in general, are discussed, in terms of surface texture and surface integrity [18]. Surface texture is a term used to describe the exterior features of the surface such as surface roughness, lay, and pits etc., while surface integrity is defined as the inherent condition of a surface layer, which pertains to properties such as micro-structural transformations, hardness alternation, residual stress distribution etc. The investigation of both surface texture and surface integrity of materials after peening will provide useful information on the states of materials, which will be later employed for the fatigue performance study.

2. MATERIAL AND METHODS

The aluminum alloy 7075-T6 was employed in this study. The Al7075-T6 has an elastic young modulus of 72 GPa, a yield strength and ultimate tensile strength of 516 and 587 MPa, respectively. The waterjet peening studies were performed on two types of test specimens: the 64 mm thick plate and 6.3mm diameter circular cross section test specimens.
The waterjet peening process involves accelerating water to very high velocities with the high intensifies pump before accelerating the water out of the nozzle to impact against the surface. Figure 1 schematically shows the parameters relevant to waterjet peening in this study. Jet velocity at the nozzle exit can be calculated using Bernoulli’s law:

\[ V_j = \sqrt{\frac{2P}{\rho}} \]  

where \( \rho \) is the density of the water. The high-pressure waterjets coming out of the nozzle are considered to contain the kinetic energy, which can be calculated by [19]

\[ E = \frac{1}{2} m_w V_j^2 \]

where \( m_w \) is the resulting mass of the water, which is equal to \( \rho A_n V_j T_e \), and \( A_n \) is the cross section area of the nozzle, and \( T_e \) is the exposure time of the jets on material surface.

The waterjet peening system employed a high-pressure pump with control unit, capable of generating waterjet pressures up to 400 MPa. The pressurized water was directed through a 0.3-mm diameter sapphire orifice before entering a nozzle specially designed for the purpose of waterjet peening. The nozzle was oriented perpendicular to the surface of the test specimen. With the test specimen fixed in a holder, the nozzle was moved and adjusted to obtain an appropriate nozzle-to-surface standoff distance, X (Figure 2). Table 1 listed the peening conditions. Number of passes and nozzle feed speed were varied to observe the effect of jet energy on material surface.

As received and waterjet peened surfaces were examined using SEM and optical microscopy to investigate surface characteristics. The surface texture resulting from the machined and peened samples was measured using contact profilometry with a commercial profilometer and 5\( \mu \)m stylus. All measurements were obtained according to ANSI B46.1-1986 [17] using a 0.8 mm cutoff length and 3.5 mm traverse length. Conventional roughness parameters, including the arithmetic average roughness (\( R_a \)), peak to valley height (\( R_y \)), root mean square roughness (\( R_q \)) and ten-point height (\( R_z \)) were calculated from each profile. Various statistical and random process methods were used in addition to standard roughness parameters to analyze the peened surface characteristics.

3. RESULTS AND DISCUSSIONS

The implementation of two (round and fan-jet) nozzles for waterjet peening played an important role on the peened surface condition. Surface finish, texture, the degree of induced subsurface hardness and compressive residual stresses.
3.1 Surface Examination

The surface roughness and statistical parameters data for the flat test specimens (conditions A-C) using round and fan-jet nozzles are shown in Figure 3. It is evident that the water peening using the round-jet nozzle caused rougher surface than those using the fan-jet nozzle for stand-off distance greater than 36 mm. In the case of fan-jet nozzle, although the kinetic jet energy was increased, there were little changes in roughness parameters again at stand-off distance greater than 36 mm. However, at low stand-off distance (less than 30 mm) had significant effect on surface roughness parameters with fan-jet nozzle.

Peening conditions that have been implemented on the flat surface were applied to the circular cross section specimens. Note that all specimens were waterpeened using the fan-jet nozzle under the same supply peening pressure, 310 MPa (condition D). The distribution of surface roughness parameters with respect to different stand-off distances of the circular cross section test specimens are shown in Figure 4-a, while Figure 4-b shows the distribution for those with respect to different jet exposure times (the nozzle feed rates and a number of passes). All surface roughness gave similar values of the arithmetic surface roughness ($R_{a}$) and the root-mean-square (RMS) roughness ($R_{q}$), while maximum peak-to-valley height ($R_{y}$) and the ten-point roughness ($R_{z}$) were within the scatter of less than 5%. It was observed that the average surface roughness parameters obtained between peened and unpeened surface have little difference in magnitude, however, maximum peak-to-valley height ($R_{y}$) and the ten-point roughness ($R_{z}$) varied and had a minimum value at 46 mm stand off distance. Surface roughness parameters were clearly dependent on the jet exposure time as shown in Figure 4b. Best surface treating condition was associated with the jet exposure time of 0.2s and is at a stand off distance 46mm. Therefore, $R_{a}$ and $R_{q}$ values might not be the parameters that can indicate the surface characteristics or distinguish the effect of the jets on material surface.

Optical examination of peened surface was conducted and surface profile corresponding to the examined surface was analysed for each specimen to discern the waterpeened surface topography under different peening process conditions. Figure 5 showed the optical micrographs and the corresponding surface roughness profile of each specimen. It was noticed that there was surface deformation in the test specimens waterpeened at the stand-off distance lower than 43 mm in the form of pronounced machined feed marks. Little changes of surface finish are noticed in the specimens waterpeened at the stand-off distance greater than 44 mm. Increasing the peening time by varying the nozzle transverse speed and a number of jet passes showed increase in all surface parameters can be seen increasing surface damage in Figure 5b. It is found that waterjet peening under the same peening time yielded similar surface roughness parameters and surface finish, although the nozzle feed rate and a number of jet passes were different. It can be explained by that under the same peening time, the resulting kinetic energy of the jet on those specimen surfaces was equal. Results of weight loss of each specimen as compared to that of the unpeened conditions are plotted in Figure 6. The weight loss of specimens increased when the stand-off distances decreased and peening time increased.
3.2 Surface Texture

Statistical parameters i.e. surface height distribution, bearing ratio, power density spectra, auto-correlation function were applied to evaluate the randomness of the surface texture. Statistical parameters, skewness and kurtosis, for specimens waterpeened by the fan-jet nozzle and the round-jet nozzle were examined. Surface skewness is the term that defines the nature of an asymmetrical surface distribution with respect to a purely symmetric or "Gaussian" spread, while kurtosis is used to identify the relative peakedness or flatness of the distribution compared with the normal distribution. A negative skewness is ideal for bearing surfaces that require large effective contact areas and lubrication reservoirs within the valleys of the lay. Positive skewness is more effective in minimizing fatigue failures through free abrasive erosion. Metals with greater resistance to abrasive penetration would be prone to exhibit a negatively skewed surface. Materials responsive to abrasive wear are more likely to exhibit a positively skewed surface due to the reduction in wear resistant surface stress concentrations [20]. Surface height skewness and kurtosis were calculated from the surface profile data using two different types of the nozzles and are shown in Figure 7. Fan-jet nozzle peened surfaces was Gaussian and had a kurtosis and skewness nearly equal to 3 and zero. The surfaces waterpeened by the round jet nozzle skewed negatively with higher value of kurtosis as compared to those specimen waterpeened by the fan-jet nozzle. This may be due to that the round jet nozzle eroded material surface causing pits or flaws by the penetration of the jet. These pits and flaws are undesirable because they may act as a crack initiation site and may reduce fatigue life of material. Therefore, the fan jet nozzle is more suitable for waterjet peening.

Figure 8 shows the height distribution and its height cumulative distribution, corresponding to the surface profiles of the round specimens shown in Figure 5. The normal distribution is a probability function that gives the probability of the surface profile that has a certain height at any positions of the surface, while the Abbot-Firestone curve or bearing ratio is the terminology used to describe the percentage of material to air of the surface profiles at any contact surface level [20-21]. It is observed from Figure 8a that the normal distribution of the all specimens waterpeened under standoff distance from 38 mm to 48 mm (condition D) showed almost similar bearing ratio, and Gaussian properties with lower peak in the specimen waterpeened at shorter standoff distances. The specimens waterpeened at longer peening time showed a more broad range in profile height distribution, with negative skew of the peak with different bearing ratio characteristics. Moreover, the bearing area fraction decreased as the peening time increased.

The stochastic properties of the surface were further examined by using power spectral density and auto correlation relations. Figure 9 shows the typical power spectrum density (PSDF) function and the auto-correlation function corresponding to the unpeened surface and the peened surface profiles shown in Figure 5b. The PSDF curve shows that with increasing peening time and decreasing standoff distances, the spectrum weight corresponding to a peak of the curve increased with the higher frequency ($\omega/2\pi$) of the wave. Note that the inverse of the frequency in the PSDF is the period of the repeated pattern on the surface in millimeters, which can be obtained in the autocorrelation functions. The autocorrelation decreased from decreased rapidly from 1 to zero stabilized. The typical correlation wavelength of waterpeened specimens at X of 38 mm and 41 mm were identical to that of unpeened specimen which was about 50 µm. However, correlation wave length of the specimen waterpeened at longer peening time was at
about 40 µm. Comparison of the normal distribution and the bearing ratio curves in Figure 8, it becomes evident that the waterjets cause the surface rougher when peening at lower standoff distance and longer peening time. Peening using standoff distance greater than 46 mm under condition D revealed negligible changes in surface texture as compared to that of the unpeened surface.

### 3.3 Surface and Sub-Surface Microstructure

Micro hardness measurements made on peened flat surfaces are shown in Figure 10. Results obtained from micro hardness measurement showed that a maximum increase in micro hardness of specimen waterpeened using the fan-jet nozzle was about 30 % greater than that of the base material. In contrast, there was less improvement of the micro hardness in waterpeened by the round-jet nozzle.

Compressive residual stress measurement was made on specimen surface by x-ray diffraction method. The residual stress results obtained from the specimens waterpeened by both the fan-jet nozzle and the round-jet nozzle are depicted in Figure 11. Results did show that waterjet peening induced the compressive residual stress in material surface. It was found that the degree of induced surface residual stress by the round-jet nozzle was greater than that of the fan-jet nozzle (Figure 11a). An increase in jet exit pressure and a decrease in a nozzle-to-surface distance increased the compressive residual stresses. Although the degree of surface compressive residual stresses induced by the fan-jet nozzle was generally lower than those by the round jet nozzle, it appears that waterjet peening by the round jet nozzle tended to cause rougher surface or greater surface erosion with little improvement of the subsurface micro hardness. As a result, the fan jet nozzle was chosen for conducting for further study on waterjet peening. In comparison to those in the unpeened specimen, all those specimens exhibited an increase in compressive residual stresses. The magnitude of residual stress was found to increase when the standoff distance increased with the magnitude lies between 200 MPa to 600 MPa. The results of induced compressive residual stress by waterjet peening in this study were in agreement with those obtained in shot peening by Was et al [3]. Moreover, increasing peening time, the compressive residual stress decreases as shown in Figure 11b. This might be due to the presence of the significant mass removal that was detected in the specimens as discussed in previous section.

### 4. CONCLUSION

Results from the investigation of surface characteristics showed that changes of surface produced by high-pressure waterjets were strongly dependent of peening parameters. It was found that waterjets did induced plastic deformation on material surface. A decrease in compressive residual stress was expected at longer peening time and shorter standoff distance when material removal occurred. Statistical functions have been used to distinguish and define appropriate standoff distance for waterjet peening. Results also showed that the changes in surface roughness and topology are directly influenced by the kinetic energy that has been transferred to target material. Therefore the same surface characteristics on the target material are obtained by
using an equal amount of energy supplied by the jet. These results might be the useful information in waterjet peening application and further study.

5. REFERENCES


Table 1: Waterjet Peening Conditions

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<tr>
<th>Condition</th>
<th>P (MPa)</th>
<th>Vj m/s</th>
<th>X (mm)</th>
<th>Vt mm/s</th>
<th>No. of Jet Pass</th>
<th>Te (s)</th>
<th>Ek (kJ)</th>
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Figure 1. A Schematic Representation of Waterjet Peening Parameters [7].
Figure 2. Waterjet peening operation on (a) a flat specimen and (b) a circular cross section of round specimen.

Figure 3. Surface Roughness Distribution (Condition A – C).
Figure 4. (a) Surface Roughness vs. $X$ of Condition D (circular cross section fatigue test specimens), $V_T = 12.7$ mm/s, (b) Surface Roughness vs. $T_e$ ($X = 48$ mm).

Figure 5. (a) Micrographs and corresponding surface profiles, peening condition D: (a-1) $X = 31$ mm, (a-2) $X = 41$ mm, (a-3) $X = 43$ mm, (a-4) $X = 46$ mm, and (a-5) = 48 mm.; (b) Micrographs and corresponding surface profiles, peening condition D, $X = 48$ mm: (b-1) $V_T = 12.7$ mm/s, $n=4$ ($T_e=0.21$s), (b-2) $V_T = 1.27$ mm/s, $n=4$ ($T_e=1.04$s), (b-3) $V_T = 1.27$ mm/s, $n=40$ ($T_e=1.04$s).
Figure 6. (a) Weight loss ($\Delta w$) vs. X, condition D ($V_T = 12.7$ mm/s), (b) Weight loss ($\Delta w$) vs. $Te$.

Figure 7. Skewness vs. Kurtosis (Conditions A and B).
Figure 8. Typical height distribution and corresponding bearing ratio curve: (a) P= 310 MPa, $T_e$=0.21 s/mm (b) P= 310 MPa, SOD = 41 mm.
Figure 9. Power spectrum density function and autocorrelation function, condition D (a) unpeened surface, (b) X = 38 mm, Te = 0.21 s, (c) X = 41 mm, Te = 1.04 s (d) X = 41 mm, Te = 1.04 s.
Figure 10. Typical micro hardness distribution.

Figure 11. (a) Residual Stress vs. X, condition A-C (b) Residual Stress vs. Te (Condition D), X = 28 mm.