2001 WJTA American Waterjet Conference
August 18-21, 2001 • Minneapolis, Minnesota

Paper **26**

ULTRA HIGH PRESSURE WATERJET PEENING

PART II: HIGH CYCLE FATIGUE PERFORMANCE

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ABSTRACT

Waterjet peening has recently emerged as one of the alternative surface treatment processes to improve the fatigue life of the components. Part I of this experimental study has been concentrated on surface characteristics of waterjet peened material. In this part of the study, un-notched hourglass shaped circular cross section test specimens were fabricated and surface treated for selected waterjet peening conditions. Completely reversed rotating bending fatigue tests were conducted on peened aluminum specimens to evaluate fatigue performance (S-N curves). Fracture surfaces were evaluated by scanning electron microscopy (SEM) to identify the fatigue mechanisms. Results show that waterjet peening can enhance the fatigue strength by 20-30% to that of unpeened Al7075-T6 material.

1. INTRODUCTION

Alternative surface treatment processes to shot peening called waterjet peening have been recently introduced using high-pressure waterjets to impinge the material surface. The development of this process was realized from the concept of jet breakup that was observed in the jet structure. Generally, high-pressure jets have the continuous solid flow characteristics in the initial region or at short distance from the nozzle exit. At longer distance, the jets, which stay coherent in the initial region, will start to breakup into a number of droplets. The impingement of each droplet is found to generate force acting normal to the surface [1]. This high force induced plastic deformation in the surface and near surface layers of the workpiece material thereby producing compressive residual stresses and increasing subsurface work hardening [1-9].

Shot peening studies [10-14] have shown that induced compressive residual stresses are beneficial to fatigue life of the components. In general, improvements of the fatigue strength by the peening process could be achieved if compressive residual stresses and work hardening were sufficiently induced in the layer of the workpiece material. The degree of fatigue improvement by the peening process, however, is strongly dependent on many factors i.e. the magnitude of induced residual stresses and the resulting surface finish. It is known that the main limitation of shot peening is a high degree of resulting surface roughness on target material. Surface alternations such as microcracks can be anticipated in the peening operation. Metallurgical studies and fatigue testing revealed that the microcracks can act as crack nucleating sites in fatigue resulting in the degradation of fatigue strength. It has been reported that the shot peening process improved fatigue strength by 25~55% in reversed bending fatigue cycling when a compressive residual stress approached 60% of material's ultimate tensile strength in high strength aluminum alloys [16]. Al-Obaid [17] also revealed that the maximum residual stress was developed at the surface for soft material while the maximum compressive stress was observed at about 125~250 μm below the surface for hard materials in general or for soft materials peened at high peening intensity or impact energy. Several recent investigations [1,3-7] have revealed that waterjet peening produced similar processing and performance results as conventional shot peening. Most of these studies were conducted either using low to moderate pressures or using round nozzles. However, published literature available on waterjet peening using fan-jet nozzles was limited.

Therefore, an experimental investigation of waterjet peening with fan-jet nozzles was conducted to further explore the potential application of this process. In the first part of this waterjet peening study, we have shown the effects of waterjet peening process conditions on material surface topography. Peened surface characteristics were evaluated and suitable peening conditions have been identified. The intent of this paper is to report the effects of waterjet peening on fatigue strength in 7075-T6 aluminum alloy.

2. EXPERIMENTS AND PROCEDURES

The test material was 7075-T6 aluminum alloy whose yield strength and ultimate strength are 516 and 587 MPa respectively [18]. Test specimens were fabricated into hourglass, circular cross section as per specification recommended in the instruction manual for RR Moore machine [19] and is shown in Figure 1. After fabrication, the gage section of each test specimen was surface treated by waterjet peening according to the process conditions listed in Tables 1. The process conditions chosen in this experimental investigation based on the results from previous study. Note that the peening time, T_e of each condition was the jet exposure time calculated per the nozzle diameter and jet traverse speed using $T_e = n\frac{D_n}{V_T}$, where n is the number of jet passes, D_n is the nozzle diameter, and V_T is the nozzle traverse speed.

The waterjet peening system employed a high-pressure pump with control unit, capable of generating pump pressures, P, up to 400 MPa. The pressurized water was controlled and directed through a 0.3-mm 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 while the test specimen was rotated with the speed of 500 RPM. An appropriate nozzle-to-surface standoff distance, X, was obtained by moving and adjusting the nozzle.

Both peened and unpeened test specimens were fatigue life tested in completely reversed rotating bending ($R = S_{min}/S_{max} = -1$) until fracture. A commercial R.R. Moore rotating bending fatigue test machine (4-point flexure) was used at rotational speeds up to 10,000 RPM at alternating stress, S, that ranged from 200 to 430 MPa. The number of cycles to fracture along with corresponding applied stress amplitude were recorded for each test for later analysis. As received and waterjet peened surfaces were examined prior to fatigue testing using SEM to discern distinguishing surface features. Fracture surfaces of failed test specimens were examined both by optical and scanning microscopy to assess the mode and origin of fatigue failure.

3. RESULTS

3.1 Surface and Sub-surface Characteristics

Figure 2 shows the surface roughness parameters obtained from the surface profiles recorded in this series of experiments. Note that the changes in the arithmetic average surface roughness (R_a) and the root-mean-square (RMS) roughness (R_q) are negligibly small between peened and unpeened specimens. However, the maximum peak-to-valley height (R_y) and the ten-point average roughness (R_z) magnitudes were greater in peened specimens as compared to as-machined or unpeened specimens. It is interesting to see that the small change in values of surface roughness parameters in the peened specimens as compared to the unpeened specimens might be the result of deformation induced during watejet peening process.

SEM micrographs of the specimen surfaces, which were water peened using nozzle-1, under the lowest standoff distance with varying supply pressures are shown in Figure 3. Peened surfaces clearly revealed no sign of surface erosion even at high-pressure used in this series of experiments. In contrast, the results obtained with nozzle-2 showed that there was erosion damage induced by the jets on the specimen surface of Set 5-6 as can be seen in Figure 4. However, the typical hardness profiles of the surface damage specimens (Set 5-7) showed an increase in surface micro hardness as shown in Figure 5.

3.2 High cyclic fatigue life

Fatigue life (S-N) curves of the hourglass, circular cross section fatigue life specimens under three different jet pressures using nozzle-1 are shown in Figure 7. It can be seen that waterjet peening improved the fatigue limit of 7075-T6 aluminum alloy. Fatigue limit or the endurance strength was evaluated for 10^8 fatigue life cycles. The maximum improvement of the fatigue limit in 7075-T6 aluminum alloy was about 25% higher than that of as-machined specimens. This improvement was found with the specimens waterpeened at P=310 MPa and X =44 mm (Figure 6). Waterjet peening at some conditions such as low pressure or those waterpeened at greater standoff distances showed little fatigue improvement even though there were no changes in surface roughness of these specimens. Moreover, by increasing the pressure and peening time (decreasing nozzle transverse speed, V_T) may yield an increase in surface hardness (Figure 5), but fatigue limit will rapidly degrade when surface erosion or damage presented. Indeed, the surface erosion induced in specimens peened by nozzle-2 clearly reduced the fatigue lives as shown in Figure 7. Therefore, nozzle and jet characteristics will have a significant effect on peening in addition to pressure and peening time.

3.3 Fatigue crack origin

Fractographic examination of fracture surfaces of both peened and unpeened test specimens were conducted. The typical SEM micrographs are shown in Figure 8. It can be seen from the micrographs that crack was initiated from the outer surface of the as-machined test specimen whereas the fatigue crack initiation site was located about 100-200 µm beneath the surface in the water peened specimens. The extent of the waterjet peening deformation layer was clearly a function of supply pressures as shown in Figure 8b-d. The greater the applied pump pressure, the deeper the surface hardening layer and the fatigue crack initiation sites.

4. DISCUSSIONS

Apparently, the degree of fatigue improvements was strongly dependent on peening conditions as observed in the S-N curves. The maximum improvement of the fatigue limit in 7075-T6 aluminum alloy was about 15-25%. Comparing this water peened alloy fatigue limit to that of published data [20] on fatigue limit of 160 MPa found for rotating and bending shows about 43% of improvement. The degree of fatigue life improvement achieved by waterjet peening in 7075-T6 aluminum alloy is less than that in case-hardened steel [1]. However, it is expected that the materials with greater tensile strength tend to have greater fatigue benefit from the peening process [16].

Fatigue test results shown in Figure 7 revealed that localized surface irregularities such as eroded pits induced by the jets could serve as very effective stress concentrations at the specimen surface. Although waterjet peening did induce deformation at the surface, but the induced deformation degraded rapidly without significant effect on the sub-surface as observed in specimens Set 5-7. Therefore, the critical concern and a word of caution is noted in waterjet peening is to minimize the stress concentrations posed by surface erosion and localized deformation.

Results from SEM micrographs showed that there was no erosion on the surface due to the jets in specimens Set 1-3. However, surface roughness data showed that the R_y and R_q roughness values of the waterpeened specimens were about 4 times higher than those of as-machined specimens. The high values of surface roughness might be the results from machining operations or localized plastic deformation. In general, an increase in surface roughness might affect the components by reducing their fatigue limit. The higher the surface finish, the lower the fatigue limit of the components. Nevertheless, with the increase in surface roughness in the waterpeened specimens, the fatigue limit did increase appreciably due to surface hardening. Therefore, we are currently examining the direct effect of waterjet peening on fatigue life improvement by considering a correction factor for interactions of surface finish, and depth of subsurface layer and will be reported in future.

5. CONCLUSION

Fatigue performance study of waterjet peened specimens under ultra-high pressure conditions by using a fan-jet nozzle was conducted on 7075-T6 aluminum alloy. Within the experimental conditions used in this study, the following conclusions were made:

1. Waterjet peening is capable of inducing surface plastic deformations similar to shot peening. Plastic deformation in waterjet peened test specimens caused fatigue crack to initiate in the interior of test specimens.

2. The degree of fatigue life improvement by waterjet peening was found to be dependent on peening conditions i.e. jet pressure, standoff distance, nozzle type, jet velocity and peening time. This study showed that the fatigue improvement by waterjet peening could be achieved.

3. Surface erosion and pits induced due to the impact of the jets has a marked influence on fatigue strength of material. To improve fatigue strength by waterjet peening, it is important that peening conditions must be appropriately chosen to ensure that waterjets will not induce surface erosion.

4. The maximum fatigue improvement found in the waterpeened specimens of high strength alloy (Al-7075-T6) was about 25 %, which is comparable to that of shot peened specimens of the same material.

6. REFERENCES

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Table 1. Waterjet Peening Conditions of Circular Fatigue Test Specimens.

Set	P (MPa)	V (m/s)	X (mm)	V_T (mm/s)	Number of jet passes, n	Peening Time, Te (s)	Nozzle Type
1	103	454	24	12.7	4	0.10	Fan (Nozzle-1)
2	103	454	36	12.7	4		
3	207	643	36	12.7	4		
4	310	787	44	12.7	4		
5	310	787	60	4.2	4	0.31	Fan (Nozzle-2)
6			64	4.2		0.31	
7			64	12.7		0.10	

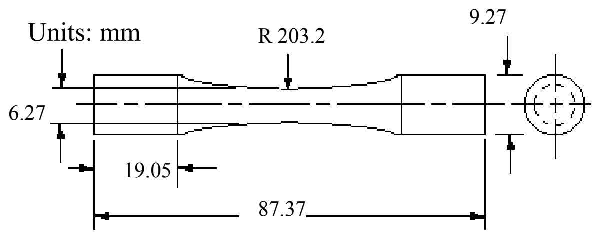


Figure 1. Geometry and Dimensions of Hourglass, Circular Cross-section Fatigue Life Test Specimens.

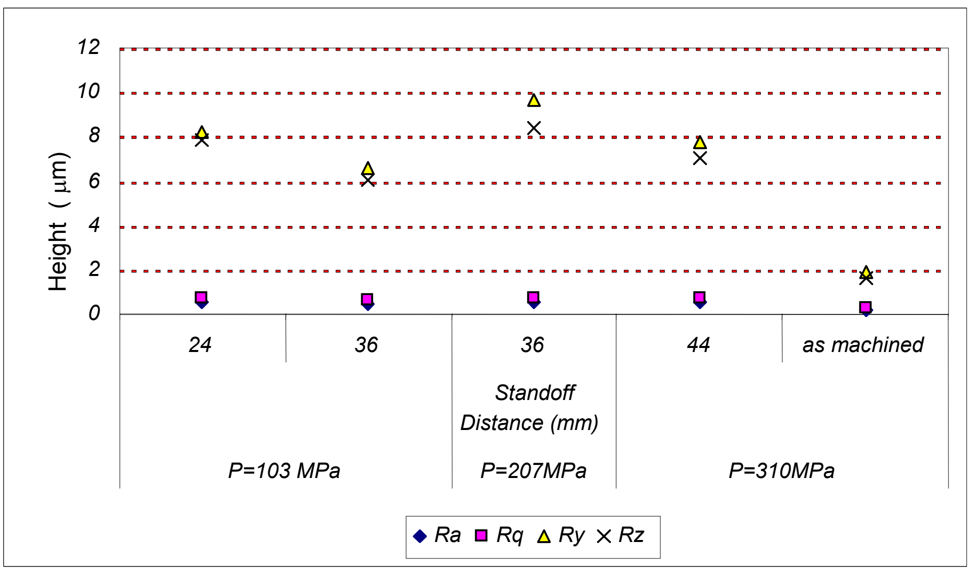
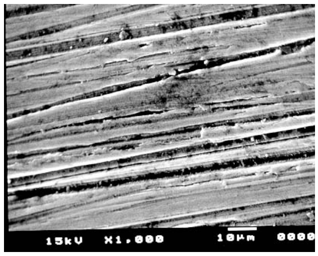
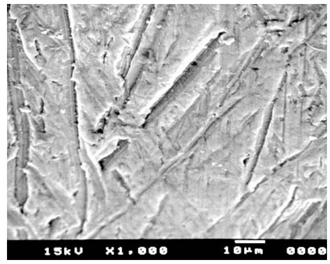


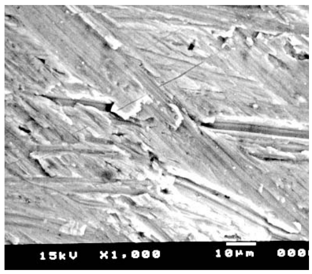
Figure 2. Average surface roughness parameters obtained on waterjet peened specimen surfaces.



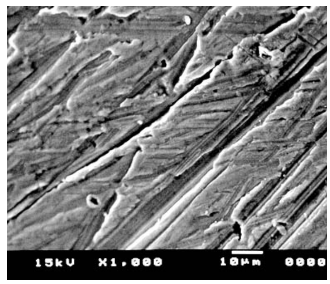
(a) unpeened surface



(b) P = 103 MPa, X=24mm.

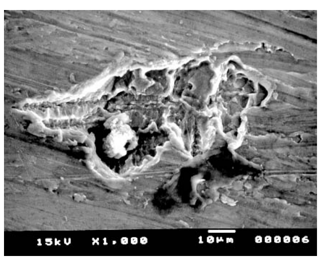


(c) P = 207 MPa, X=24mm.

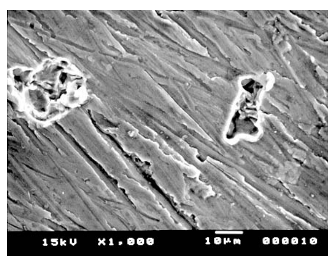


(d) P = 310 MPa, X=44mm.

Figure 3. SEM Micrographs of Fatigue Specimen Unpeened and Peened Surfaces at Different Applied Pressures using Nozzle-1.



(a) P = 310 MPa, X=60mm
Te = 0.31 s



(b) P = 310 MPa. X=64mm
Te = 0.31s

Figure 4. SEM Micrographs of Fatigue Peened Surfaces using Nozzle-2.

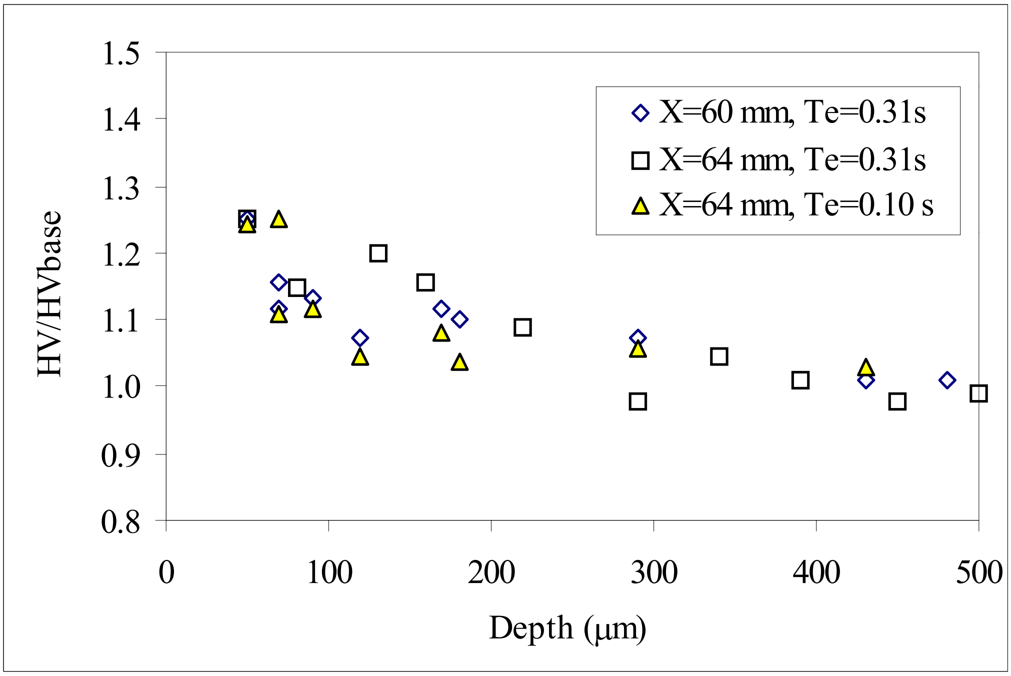


Figure 5. Hardness Distribution of Waterpeened Specimens (Set 5-7, P=310 MPa).

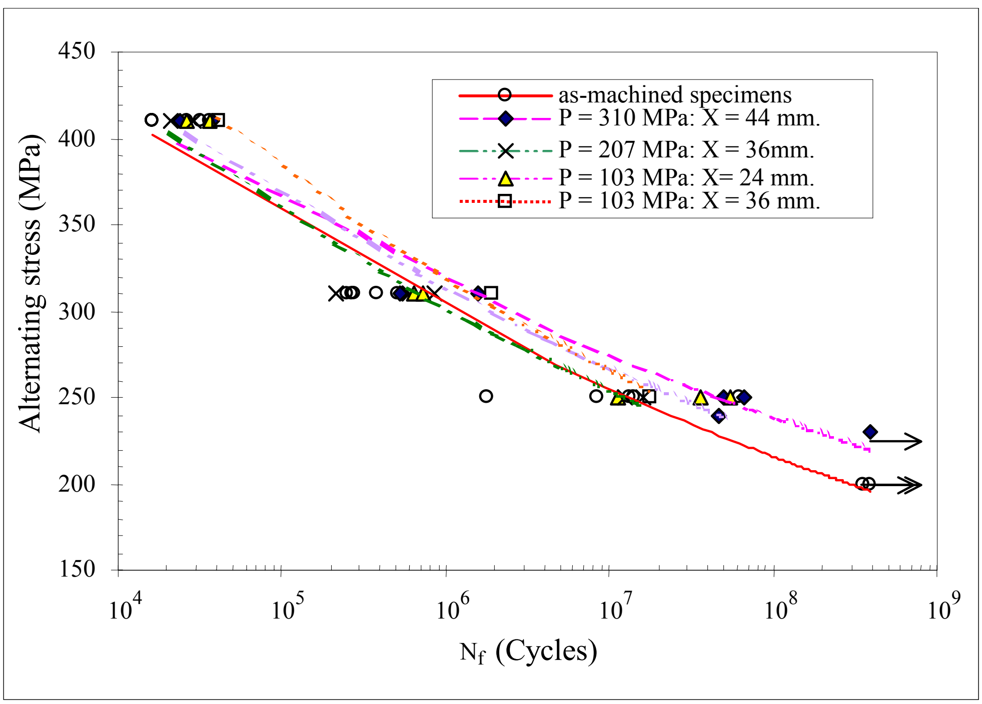


Figure 6. S-N Curves of the Waterpeened Specimens, Set 1-4 using Nozzle-1.

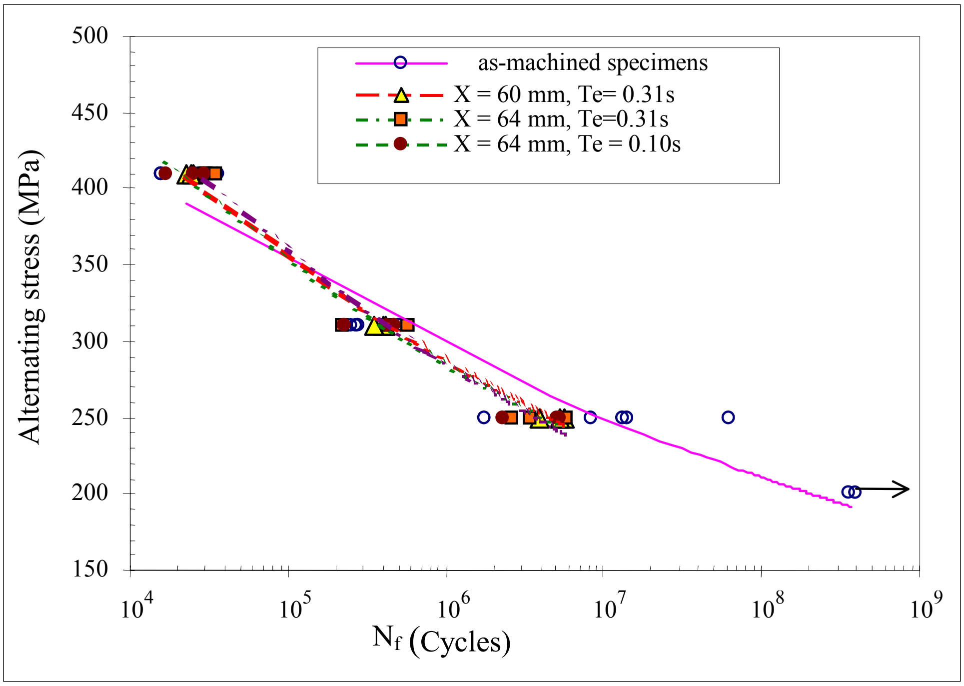
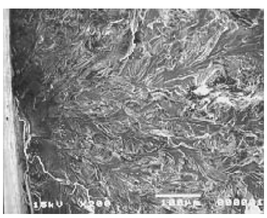
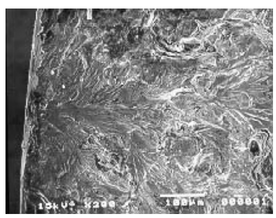


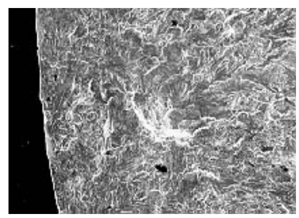
Figure 7. S-N Curves of the Waterpeened Specimens, Set 5-6 using Nozzle-2.



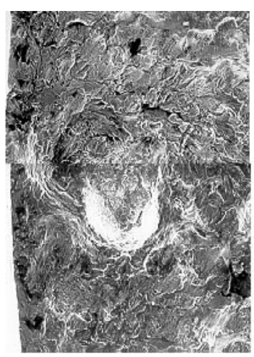
(a) unpeened



(b) waterpeened (P = 103 MPa)



(c) waterpeened (P=207MPa)



(d) waterpeened (P = 310 MPa)

Figure 8. SEM Fractography of Fracture Surfaces Tested at Mean Stress = 250 MPa.