Engineering Failure Analysis 92 (2018) 268–277

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

A study on the compressive residual stress due to waterjet cavitation peening

K. Balamurugan[a], M. Uthayakumar[b,*], S. Gowthaman[c], R. Pandurangan[d]

[a] Department of Mechanical Engineering, VFSTR (Deemed to be University), Guntur, AP, India
[b] Faculty of Mechanical Engineering, Kalasalingam University, Krishnankoil, India
[c] Department of Applied Engineering, VFSTR (Deemed to be University), Guntur, India
[d] Tractor and Farm Equipment Ltd, Chennai, India

ARTICLE INFO

Keywords:
Residual stress
Fatigue
Cavitation
Hardness
Surface morphology

ABSTRACT

The repetitive cyclic loads on the forming tool tend to fatigue failure. Molybdenum-based high-speed steel forming tool is extensively used for producing bevel gears but, often failure occurs at the root of tooth zone. To increase the tool life, an attempt has been made to provoke beneficial compressive residual stress on the root surface of form tool by waterjet turning cavitation peening process.The cavitation peening operation is done in the forming tool by directing the high-pressure waterjet of 27 MPa to the root section of the teeth region. The cavitation operation is governed by the system parameters like waterjet pressure at the nozzle exit, stand-off Distance, nozzle angle and the processing time per unit length. The residual stress induced on the sample is confirmed through X-ray diffraction technique and the effects of beneficial residual stress are measured at different operating conditions on hardness and surface profile and they are compared with the nascent sample. The study reveals that lower operating levels of Stand-off distance, nozzle angle of 45° induce more compressive residual stress around tooth region with less distortion at the surface profile. The waterjet impinged surface is observed through microscopy examinations and evaluated.

1. Introduction

The applications of waterjets are in the range from cleaning to cutting in different fields like construction, maintenance, and manufacturing industries. Among the different applications of waterjets, water jet peening is a novel surface treatment process that has gained momentum in the recent past, due to certain unique characteristics. Soyama et al. [1] investigated the influence of jet pressure and the nozzle geometry of the cavitation peening and reported that the water hammering effect due the impingement of water particle was found to be responsible for the surface erosion. Sadasivam et al. [2] delivered that with the force-controlled treatment, it became inevitable to induce compressive residual stresses inside the top surface layers with negligible deformation in surface topography. Ijiri et al. [3] have made an attempt to increase the cavitation rate through the induced supplementary nozzle and it yields a delay in erosion rate particularly at the center part of the workpiece.Soyama. [4] revealed that the cavitation jet air peening improves the fatigue strength more than the cavitation Water Jet Peening (WJP) and the observations confirm the improvement in fatigue strength over the non-peened samples.

Azhari et al. [5] conducted WJP studies on Al-5005 and delivered that the influences of machining parameters like water pressure, feed rate, number of passes and low standoff distance significantly determine the surface roughness and hardness of the material.

* Corresponding author at: Faculty of Mechanical Engineering, Kalasalingam University, Krishnankoil 626126, India.
E-mail address: uthaykumar@gmail.com (M. Uthayakumar).

https://doi.org/10.1016/j.engfailanal.2018.05.012
Received 13 December 2017; Received in revised form 20 May 2018; Accepted 22 May 2018
Available online 28 May 2018
1350-6307/

Nomenclature

M2HSS	Molybdenum based High-Speed Steel
AWJM	Abrasive Waterjet Machine
WJM	Water Jet Machine
WJP	Water Jet Peening
SOD	Stand-Off Distance
Ra	Surface roughness
XRD	X-ray Diffraction
LVM	low carbon vacuum melt
AA	High strength Aluminium Alloy
Sq	Root Mean Square roughness
Ssk	Skewness
Sku	Kurtosis
Sp	Maximum peak height
Sv	Maximum valley depth
Sz	Maximum height of surface
Sa	Average roughness

Srivastava et al. [6] have measured the influence of pulsed waterjet on stainless steel and found that the low jet pressure of about 20Mpa is sufficient to induce hardness and also for conversion of tensile stress to compressive stress.Zhanshu et al. [7] investigated the effects of waterjet peening parameter on Al 6061 alloy and identified that water jet hammering pressure alone has a significant impact in inducing residual stress. Soyama [8] was found that there is an increment of 51% fatigue life on duralumin plates that have fastener holes where the hole region has undergone WJP operation. Boud, et al. [9] have studied the effect of process parameters on the surface integrity of the AA7075 material and have stated that the fatigue life greatly depends on the surface roughness and the residual stress.

Chen et al. [10] through the experimental works have confirmed that WJP on titanium alloy, spring steel, and Inconel induces compressive residual stress on the top surface by 45–60%, increase stored energy by 20–200% and has no influence on the surface roughness. Han, et al. [11] stated that the fatigue strength could be increased with the prevention of crack growth initiation in the surface of the material and it could be achieved by inducing the compressive residual stress to the depth of 140 μm. Azhari, et al. [12] studied the effects of WJP parameters on the surface characteristics of carbon steel 1045 and found the change in hardness value up to the depth of 200 μm. Beyond this range, the hardness values are almost similar to the base material.

Dong et al. [13] have studied the effect of WJP in SCR420H carbon steel combined with heat treatment process and confirmed that the compressive stresses of the material inside the surface layer have uniform dispersion within the structure. Further, this action improves the life of the gears. Sadasivam et al. [14] have investigated the residual stress of titanium alloy treated with AWJP and found that the load control pre-stress improves 50% surface residual stress and 10% improvement is found in the maximum residual stress. Hashimoto et, al. [15] investigated the stability of the compressive residual stress caused by the WJP in the welded nickel alloy in the pressurized water and identified that the stress relaxation would occur, due to the regaining of the severe plastic deformation. Guian et al. [16] had studied on the crack driving forces that are produced due to the welding/cladding residual and concluded that the cracks may tend to propagate from the outer surface for cladding residual stress.

Bozic et al. [17] commented that the residual stress is an important factor while in determining the fatigue crack growth rate. According to Maximov et al. [18] fatigue strength to structure, irrespective of compressive residual stress, there are some other governing factors are also has a significant effect likely; smooth surface profile, the microstructure of the surface. Lieblich, et al. [19] made a comparative study of the fatigue behavior of biomedical titanium alloy treated with WJP and grit blasting. It was found that the fatigue resistance of shot blasting with alumina particles was more and improved 15% hardness than the water jet peening. Azhari, et al. [20] have analyzed the effects of WJP on fatigue performance and reported that the residual stress induced into the surface is limited to 100 μm. They have also stated that the treated samples have a lower fatigue limit. Azhari, et al. [21] have also investigated the influence of water jet peening on the surface finish and the change of hardness on austenitic stainless steel 304 with multiple passes of the waterjet. It is stated that maximum hardness and less roughness can be achieved only on the combined effect of surface hardening and the multiple process steps of water jet treatment. Naito et al. [22] proposed a technique using recirculate shots accelerated with high-pressure water jet on the surface of the stainless steel and found that compressive residual was introduced up to 600 μm depth. This will increase the fatigue strength by 25% compared to the unpeened surface.

According to Xie and Rittel [23], Pure waterjet machining is found to be compromising technique to import residual stress on the surface of the sample with least surface distortion. Abhishek et al. [24] performed surface modification treatment for thermal relaxation on Inconel 718 by using laser shock peening, cavitation peening, and ultrasonic nanocrystalline surface modification technique and results confirm that the most thermal relaxation factor is removed by the cold working process. Farayibi, et al. [25] introduced a new surface modification technique as plain water jet peening tailed by pulsed electron beam irradiation for the laser clad surface of titanium alloy. The least surface distortion is produced on plain water jet milling and it tends to get increases with the increase of a number of passes. Barriuso, et al. [26] compared the WJP of AISI 316 LVM material and the titanium alloy. The results showed that the WJP could increase the surface hardness to 300 HV from 210 HV and the hardness beneath the surface also increased up to 100 μm. Ijiri et al. [27] evaluated the microstructure and the hardness on Cr-Mo steel machined by waterjet peening had concluded that due to cementite protrusions in pearlite grains tends to form voids in the area of 0.5–1.0 mm whereas there is no such signs are found beneath the surface.

Inducing compressive residual stresses into the surface layer will enhance the fatigue strength characteristics of the material. The objective of this work is to provoke beneficial compressive stress to a hardened M2HSS tool by means of abrasive waterjet cavitation peening. This forming tool is used to produce bevel gears. Repetitive cyclic load results in fatigue failure and the analysis proven that fatigue cracks are initiated at the root of tooth zone. The crack tends to propagate and ultimately tool failure after some cyclic application of load. To increase the tool life, waterjet cavitation peening operation is performed at the root section of the teeth. The resulting residual stress is evaluated by X-ray Diffraction (XRD). Analysis of the induced section shows an affordable compressive residual stress is induced deeper into the tooth route area. Further, the influences of the working parameters on the hardness, the amount of residual stress induced on the top surface of the samples and the surface defects are analyzed.

2. Materials and method

2.1. The material

M2HSS form die tool is used to manufacture pinion bevel gears in IP Rings Ltd., Chennai Due to the repetitive cyclic load, the tool tends to have fatigue failure. The failure analysis reports that the tool failure occurs at the root area of the tooth region and the region where the failure initiation is shown by indication in the Fig. 1. The cylindrical test sample of diameter 68 mm and length 40 mm is taken for experimental work. The composition of die steel is given in Table 1.

2.2. Machining process

WJP is carried out on nascent samples by using waterjet machine model DIP 6D-2230 that has aworking pressure of 27 MPa with the flow rate of 3.1lts/min. For experimental observations SOD of 60, 25 and 10 mm and nozzle angle of 30°, 45° are identified as input operating conditions. The processing time per unit length is fixed as 35 s/mm for all the experimental conditions. The schematic diagram of waterjet peening experimental setup is shown in Fig. 2.

2.3. Experimental details

A fixture is designed and developed with the motorized arrangement to hold the sample. The detailed layout of the fixture and its experimental set up are shown in Fig. 3.

The sample is mounted on three jaw chuck and is completely submerged in water. The nozzle is aligned to the required angle and SOD is also aligned to avoid the waterjet impinges especially on the root region. The chuck is power driven and the water is allowed to hit the region for the fixed time. The experimental parameters of AWJM are shown in Table 2. The continuous bombardment of the air bubbles on the rotating sample is caused to enhance the residual stress on the surface. During the machining process, the high-pressure waterjet creates air bubbles and these bubbles along with the forced waterjet will help in importing the residual stress and hardness on the surface of the sample.

2.4. Characterization study

Hardness is defined as the resistance to indentation and it is an important mechanical property that determines the functional property of the material. Vicker's hardness tester is used to find the characterization of the peened surface. The hardness test is performed using a fixed load of 1 N for a dwell period of 10 s. Hardness is calculated by using the Eq. (1).

$$\mathrm{HV} = \frac{1.854P}{d^2} \tag{1}$$

where P, HV, and d have applied a load, Vickers hardness, and average diagonal length, respectively.

The surface roughness of a die plays a major role to get good quality forged product material. The surface profile of the sample is measured by using a surface roughness tester of Mitutoyo SJ410 that has a range of 350 μm with a probe speed of 0.25 mm/s and over a cut-off length of 5 mm. A minimum of five observations are taken and the average of the close repetitive observations are recorded.

Residual stresses are stresses that are present in a material even after the source of stress caused are removed. Here, X-ray

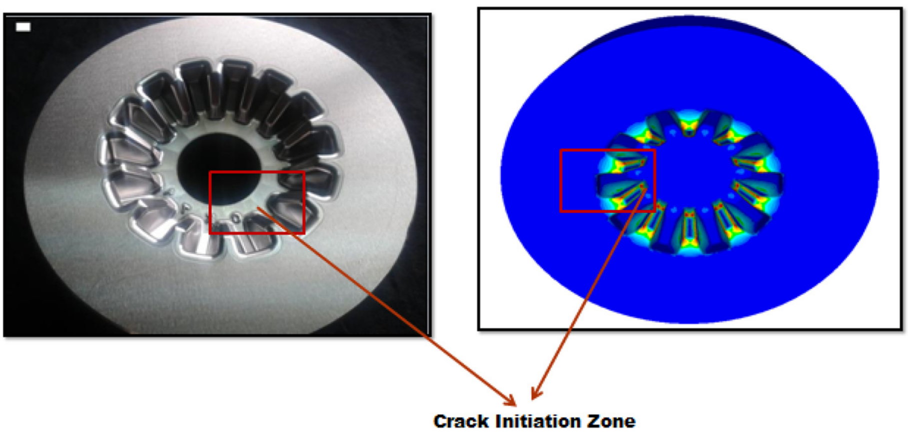

Fig. 1. M2HSS forming die with highlighted tooth region where the crack initiates.

Table 1
Composition of die steel.

Elements	C	W	Mo	Cr	V	Fe
Weight %	0.85	6	5	4	1.9	Rest

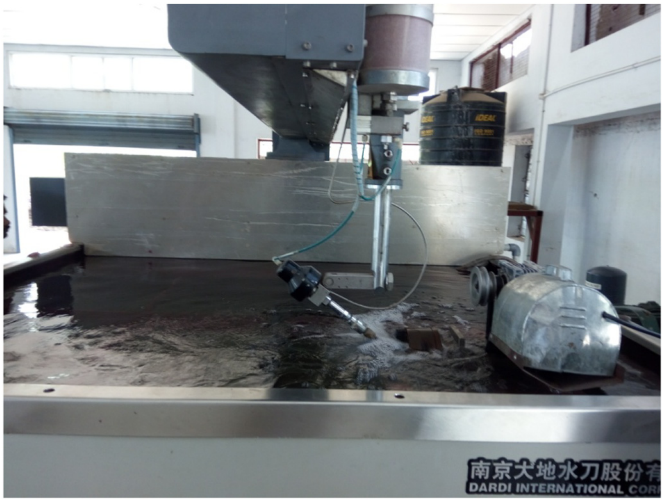

Fig. 2. Experimental setup of AWJM.

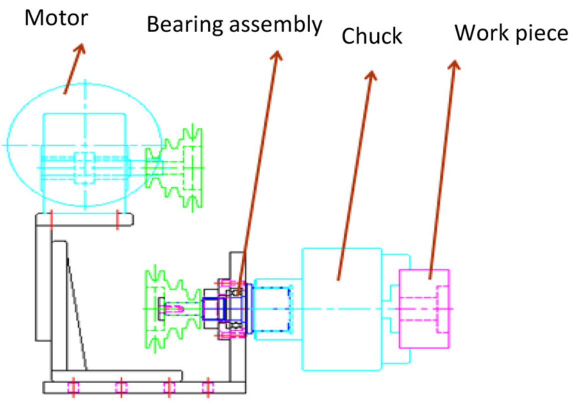

Fig. 3. Chuck assembly design.

Table 2
Experimental parameters of AWJM.

S. no	Input parameters	Unpeened sample	S1	S2	S3	S4	S5	S6
1	Waterjet pressure (MPa)	–	27	27	27	27	27	27
2	SOD (mm)	–	60	60	25	25	10	10
3	Nozzle Angle (Deg)	–	30	45	30	45	30	45
4	Processing time per unit length (sec/mm)	–	35	35	35	35	35	35

diffraction technique is used to determine the residual stress imported on the sample. The residual stress is measured by the distance between the crystallographic planes. If the material is under compression, the observation of "d" spacing will fall down and an increasing effect is observed on the tensile test. The XRD parameters are used to calculate the residual stress and they are listed in Table 3. The induced residual stresses on the peened and unpeened samples are calculated by using the Eqs. (2) to (5).

$$\varepsilon = \frac{d - d_0}{d} \tag{2}$$

Table 3
Parameters for residual stress measurement.

S.no	Parameters	Characteristics
1	Characteristic X-ray	Cr k alpha 1
2	Diffraction plane	(211)
3	Range of ψ	−41.80° to 18.2°
4	2 - theta range	156.68° to 157.23°

$$\varepsilon = \frac{1}{2}s_2\left[\sigma_{11}sin^2\psi + \sigma_{33}sin^2\psi + \tau_{11}\sin 2\psi\right] + s_1\left[\sigma_{11} + \sigma_{22} + \sigma_{33}\right] \tag{3}$$

$$s_1 = \frac{-\nu}{E} \tag{4}$$

$$\frac{1}{2}s_2 = \frac{1+\nu}{E} \tag{5}$$

where ε, σ_{ij}, d, d_o, ν and E are strain due to peening, stress components, the space between selected crystallographic plane after and before peening, poisson ratio, youngs modulus respectively and S_1 and S_2 are constants.

3. Results and discussion

3.1. Residual stress as a function of SOD and nozzle angle

The induced residual stresses under the given operating conditions are measured and listed in Table 4. The level of residual compressive stress induced under the operating condition ranges from −12.3 to −954.3 MPa and its shown in Fig. 4. According to Srivastava et al. [28] it be could able to induce a compressive residual stress of 275 Mpa with the increase of hardness of about 9% over a depth of 50 μm while performing AWJT operation on $A359/B_4C/Al_2O_3$ hybrid composite.

The rate of induced stress decreases if SOD is increased. This is because of the reduction in impact force that ultimately leads to less dislocation formation. Through the above experimental observations, it is identified that the maximum rate of induced residual stress on the sample is superior at the nozzle angle of 45° to nozzle angle of 30° for all the cases. The impact force generated at the nozzle angle of 45° is considerably high irrespective of other parameters. The compressive residual stress will enhance the mechanical properties of any material due to its decrement in average grain diameter as per hall-petch eq. 6.

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}} \tag{6}$$

where σ_y = yield stress, σ_o = materials constant, k_y = strength coefficient and d = average diameter of the grain.

3.2. Hardness as a function of SOD and nozzle angle

Peening operations will increase the induced compressive residual stress on the surface and its results in yielding excellent hardness property of the material. The high pressure creates the cavitation effect on the surface of the sample and this is caused to get plastic deformation which leads to increase the dislocation density. The hardness observations at different operating environments are shown in Table 5.

There is a significant increment in hardness value and it is observed in the unpeened sample. Change in SOD causes the linear decrease of hardness value and is shown in Fig. 5. Irrespective of different parametric conditions, change in the levels of SOD creates a uniform decrease in hardness at both the considered point angles.

There is an increment in hardness found on a peened sample from 698 to 1058.34 HV by SOD 10 mm and nozzle angle of 45°. Peening operations will increase the induced compressive residual stress on the surface and its leads to get plastic deformation surface. This plastic deformation surfaces are formed by the reduction in the d-spacing between two atomic planes. This reduction is

Table 4
Experimental observations of residual stress.

S.no	Pressure (MPa)	SOD (mm)	Processing time/length (*sec*/mm)	Nozzle angle (deg)	Experimental residual stress (MPa)
1	Unpeened				−12.3 ± 1.11
2	27	60	35	30	−793.6 ± 2.65
3	27	60	35	45	−823.8 ± 2.87
4	27	25	35	30	−855.8 ± 4.24
5	27	25	35	45	−888.5 ± 1.92
6	27	10	35	30	−922.7 ± 2.54
7	27	10	35	45	−954.3 ± 1.22

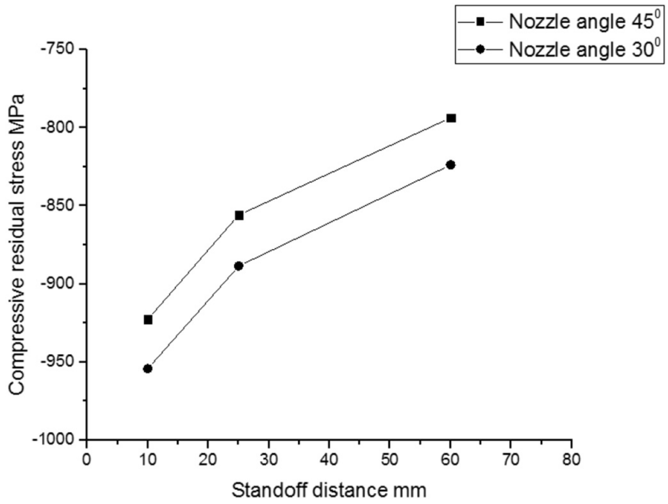

Fig. 4. Compressive residual stress as a function of SOD and nozzle angle.

Table 5
Experimental observations on Hardness.

S.·no	Pressure (MPa)	SOD (mm)	Processing time/length (sec/mm)	Nozzle angle (deg)	Vicker hardness (HV)
1	Unpeened				698.23 ± 2.12
2	27	60	35	30	812.6 ± 1.22
3	27	60	35	45	859.2 ± 0.82
4	27	25	35	30	911.3 ± 1.84
5	27	25	35	45	978.2 ± 1.11
6	27	10	35	30	1013.3 ± 1.90
7	27	10	35	45	1058.34 ± 1.02

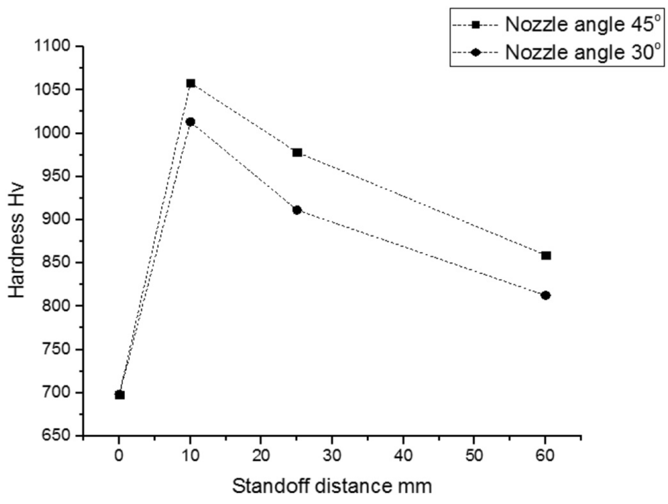

Fig. 5. Hardness as a function of SOD and nozzle angle.

directly proportional to induced residual stress. It cause grain size reduction or grain refinement and increment on dislocation density on top surface of the peened sample and it will decrease from the peened surface. It is important to discuss that waterjet peening enhance the surface hardness by invoking beneficial compressive residual stress that is induced on the top surface.

3.3. Surface roughness as the function SOD and nozzle angle

Table 6 shows the variation of the surface profile with the different operating conditioning of WJM and Fig. 6 shows the effect of Surface roughness with a change in SOD. From the above observation, it is found that the surface roughness of the sample is increased

Table 6
Surface roughness as a function of SOD and nozzle angle.

S.·no	Input parameters	Unpeened sample	S1	S2	S3	S4	S5	S6
1	Working pressure (MPa)	–	27	27	27	27	27	27
2	SOD (mm)	–	60	60	25	25	10	10
3	Nozzle angle (Deg)	–	30	45	30	45	30	45
4	Processing time per unit length (sec/mm)	–	35	35	35	35	35	35
5	Surface roughness Ra (μm)	0.110	0.32	0.36	0.42	0.45	0.47	0.49

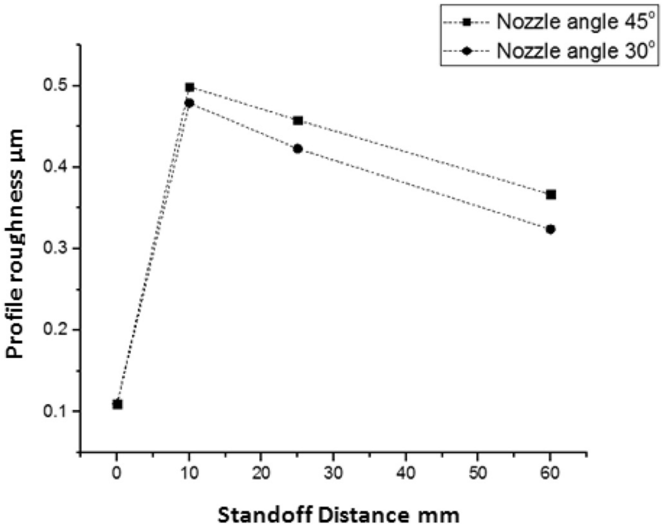

Fig. 6. Profile roughness as a function of SOD and nozzle angle

after peening due to large plastic deformation on the top surface. The surface roughness of the peened sample with a SOD of 10 mm and angle of 45° is more compared to other observed samples. The cavitation peening effect on the top surface of the sample decreases the surface roughness whereas an improvement in surface profile is obtained with increase in SOD. This is because of the divergence of the water with an increase in SOD. The level of high-pressure water, that strikes the top surface of the sample gets decreased considerably. Besides, it leads to getting the cavitation effect.

3.3.1. Surface profile analysis using 3D optical profilometer

The 3D optical image analysis is performed on the peened samples and it is shown in Fig. 7. The values of the characteristics parameters namely Sq, Ssk, Sz, and Sa are found to have an incremental value with change in the direction of the nozzle. Small dimples that are formed due to the cavitations effect can be observed all over the surface of Fig. 7(a) and the bulk depression are observed in Fig. 7(b). Increase in nozzle angle makes the air bubble to trap within the region. This action enhance the cavitation effect in the localized zone and tend to have more forging effect which results in the erosion of materials or creating the bulk deformation over the surface of the sample. Ssk skewness value is found to be negative value at both operating conditions indicates that the material deformation take place nearby the peaks.

Higher Sku value and least Ssk skewness are observed with the change in the nozzle angle of 30°. Since Sedlacek et al. [29] confirms that higher the Sku kurtosis value and lower the Ssk will lead to having low friction. Being a forging tool this property is found to be a desirable property in the present study. Nearly 30% reduction of peak height (Sp) is observed at the inclination angle of 30°. Xie and Rittel [30] reported that negative skewness obtained in the waterjet peening is due to the removal of peaks formed during the primary machining process will enhance in load-bearing capacity of the materials. Bulk erosion of materials at the 45° nozzle angle leads to having higher Sa.

3.3.2. Surface morphology analysis using SEM

The morphology of peened and upeened samples is analyzed using scanning electron microscope. From the observations, it is can be stated that the peening action tends to affect the surface profile of sample and creates more dislocation density. These dislocations will leads to having Jogs and Kinks. In order to have these extra segments in a dislocation line, it required more energy and workforce which cause to increase the hardness of the material.

Fig. 8(a) shows the unpeened sample morphology and Fig. 8(b) shows the Peened sample by SOD 10 mm and nozzle angle 30°. Fig. 8(c & d) clearly shows the plastic deformation on the peened surface due to erosion by SOD of 10 mm and nozzle angle of 45°. Fig. 8(e) shows the strengthening zone of waterjet peened sample by SOD of 10 mm and nozzle angle of 30°. Among these surface

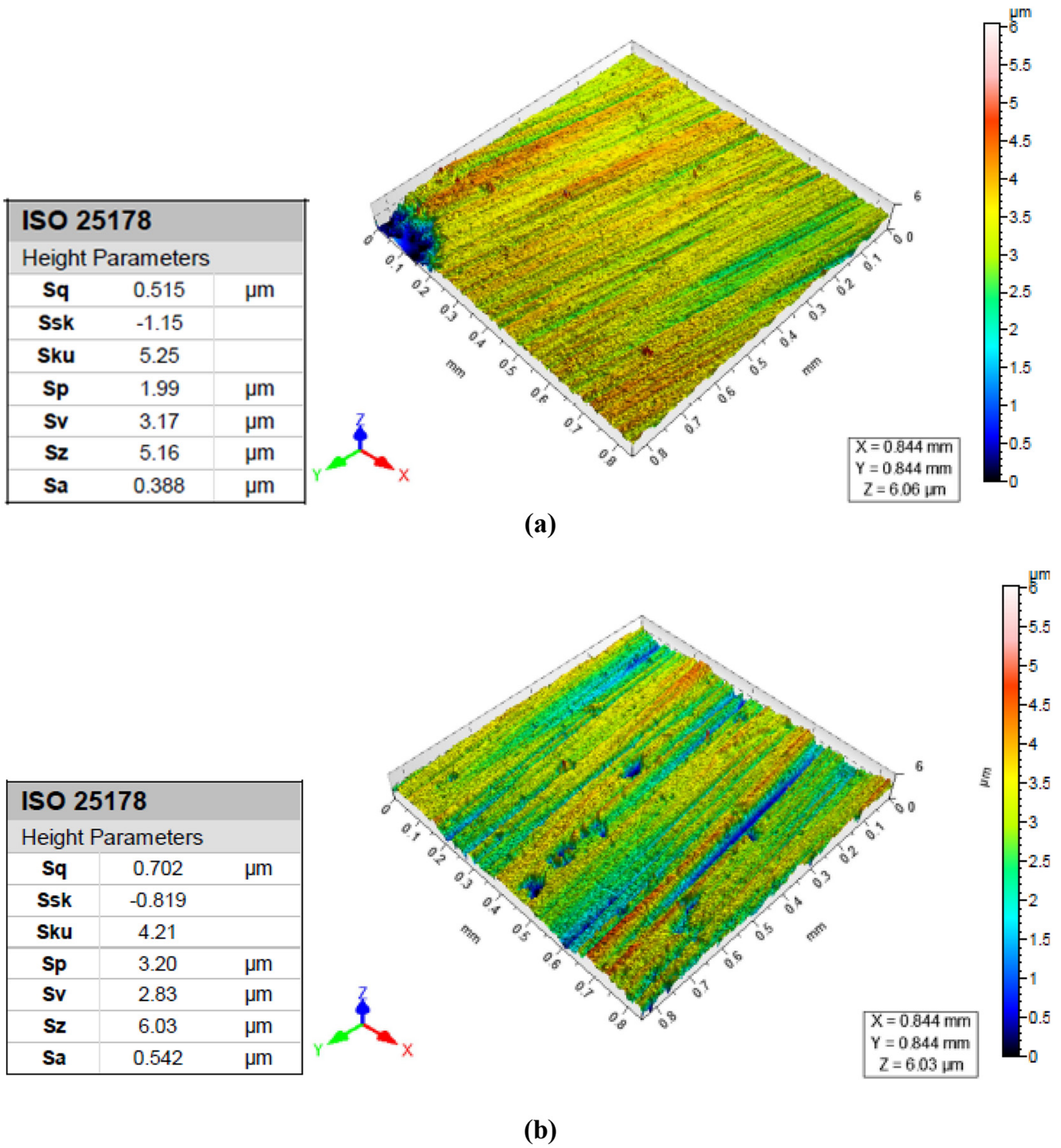

Fig. 7. Surface morphology of the peened samples (a) SOD of 10 mm and nozzle angle of 30° and (b) SOD of 10 mm and nozzle angle of 45°.

morphology images, the peened sample by SOD of 10 mm and nozzle angle of 45° has more eroded surface compared to peened sample by SOD of 10 mm and nozzle angle of 30°.

Fig. 8(e) on the sample surface is subjected to have a cavitating waterjet under high pressure with processing time per unit length of 35 s/mm. A ring mark is observed and this is formed by the plastically deformed pits, as the cavitation clouds developed by the cavitating jet are collapsed on the surface. Due to this collapse, a huge impact is generated and it produces a ring pattern with the region at the center undamaged. The size of the plastically deformed pits is more than 2 µm diameter. These pits are the main reason for the increment of surface roughness of peened sample compared to unpeened sample.

4. Conclusion

Waterjet peening operation is successfully performed on the teeth root region of M2HSS forming tool with a modified experimental arrangement in waterjet machine. The induced beneficial residual stress on the top surface of the root region is identified through X-Ray diffraction techniques. WJP and its effects on mechanical properties and surface morphology are analyzed. Residual stress and Vicker's hardness are measured on nascent and peened samples and the following conclusions are drawn.

- In WJP, the increase in compressive residual stress on the sample mainly depends on SOD and the nozzle angle. From the

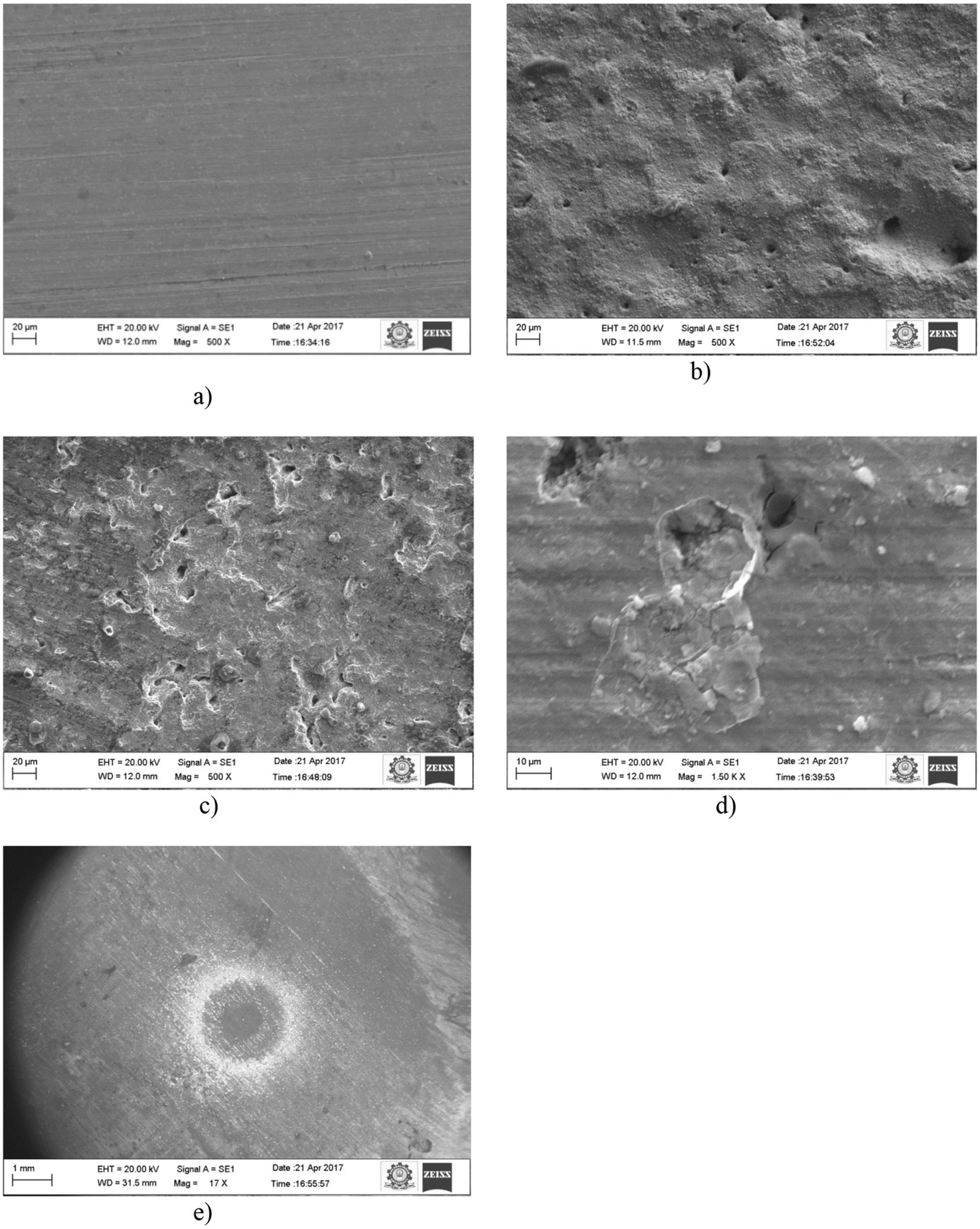

Fig. 8. SEM images of a) Unpeened samples, b) Peened sample by SOD 10 mm and nozzle angle 30°, c) Peened sample by SOD 10 mm and nozzle angle of 45°, d) Magnified view of peened sample by SOD 10 mm and nozzle angle of 45°, e) Strengthened zone of peened sample by SOD 10 mm and nozzle angle of 30°.

observation, it is noticed that the maximum value of residual stress is recorded at the nozzle angle of 45° and SOD of 10 mm.

- It is also believed that the similar effects will be observed at the nozzle angle of 60°. Hence, it is stated that to induce the considerable level of residual stress on the sample, the preferable nozzle angle is 45°.
- Waterjet peening induces residual stress on the top surface of the sample via plastic deformation. This stress increases the surface profile and leads to having more dislocation density. This dislocation density is directly proportional to the hardness. Hence it can be stated that the hardness can be related to the surface measurement and its roughness.
- WJP create plastic deformation surface by importing beneficial residual stress via micro-strain. The dislocation density is directly proportional to the square of the micro-strain and it is measured and confirmed through XRD.

- Higher Sku value and least Ssk skewness are proved to have low friction and being a forging tool this desirable property is obtained at a nozzle angle of 30° and also, nearly 30% reduction of peak height (Sp) is observed at the inclination angle of 30°.
- Through the observation, it can be stated that the M2HSS forming tool has a great potential for forging operation and it increases its lifetime by inducing the residual stress over the top surface of the sample.

Acknowledgement

The Authors submit their thanks to Centre for advanced Machining (DST-FIST), Kalasalingam University, for providing facility to carry out the research.

References

[1] H. Soyama, T. Kusaka, M. Saka, Peening by the use of cavitation impacts for the improvement of fatigue strength, J. Mater. Sci. Lett. 20 (2001) 1263–1265.
[2] B. Sadasivam, A. Hizal, D. Arola, Abrasive waterjet peening with elastic prestress: a parametric evaluation, Int. J. Mach. Tools Manuf. 49 (2009) 134–141.
[3] M. Ijiri, D. Shimonishi, D. Nakagawa, T. Yoshimura, New water jet cavitation technology to increase number and size of cavitation bubbles and its effect on pure Al surface, Int. J. Lightweight Mater. Manufac. 1 (2018) 12–20.
[4] H. Soyama, Improvement of fatigue strength by using cavitating jets in air and water, J. Mater. 42 (2007) 6638–6641.
[5] A. Azhari, C. Schindler, B. Li, Effect of waterjet peening on aluminum alloy 5005, Int. J. Adv. Manuf. Technol. 67 (2013) 785–795.
[6] M. Srivastava, S. Hloch, R. Tripathi, D. Kozak, S. Chattopadhyaya, A.R. Dixit, J. Foldyna, P. Hvizdos, M. Fides, P. Adamcik, Ultrasonically generated pulsed water jet peening of austenitic stainless-steel surfaces, J. Manuf. Process. 32((2018) 455–468.
[7] H. Zhanshu, Z. Shusen, F. Ting, C. Lei, Z. Yuanxi, Z. Meng, W. Peizhuo, Experimental and numerical analysis of water jet peening on 6061 aluminum alloy, J. Press. Vessel. Technol. 140 (2017) 21406–21417.
[8] H. Soyama, The use of cavitation peening to increase the fatigue strength of duralumin plates containing fastener holes, Mater. Sci. Appl. 5 (2014) 430–440.
[9] F. Boud, L.F. Loo, P.K. Kinnell, The impact of plain waterjet machining on the surface integrity of aluminium 7475, Proc. CIRP 13 (2014) 382–386.
[10] G. Chen, D. Zhang, J. Song, Y. Zeng, Z. Li, W. Zhou, Effect of high-pressure waterjet peening on surface strengthening properties of 7075-T651 aluminum alloy, Key Eng. Mater. 373/374 (2008) 828–831.
[11] B. Han, D.Y. Ju, W.P. Jia, Influence of water cavitation peening with aeration on fatigue behaviour of SAE1045 steel, Appl. Surf. Sci. 253 (2007) 9342–9346.
[12] A. Azhari, C. Schindler, J. Nkoumbou, E. Kerscher, Surface erosion of carbon steel 1045 during waterjet peening, J. Mater. Eng. Perform. 23 (2014) 1870–1880.
[13] X. Dong, R.Z. Guo, S.W. Song, C.Y. Zhuo, Water jet shot peening strengthening surface roughness, Adv. Mater. Res. 670 (2013) 174–179.
[14] B. Sadasivam, D. Arola, An examination of abrasive waterjet peening with elastic pre-stress and the effects of boundary conditions, Mach. Sci. Technol. 16 (2012) 71–95.
[15] T. Hashimoto, Y. Osawa, S. Itoh, M. Mochizuki, K. Nishimoto, Long-term stability of residual stress improvement by water jet peening considering working processes, J. Press. Vessel. Technol. 135 (2013) 0316011–0316018.
[16] Q. Guian, V.F. Gonzalez-Albuixech, N. Markus, Effects of Embedded Cracks and Residual Stresses on the Integrity of a Reactor Pressure Vessel, 90 (2018), pp. 451–462.
[17] Z. Bozic, S. Schmauder, H. Wolf, The effect of residual stresses on fatigue crack propagation in welded stiffened panels, Eng. Fail. Anal. 84 (2017) 346–357.
[18] J.T. Maximov, A.P. Anchev, G.V. Duncheva, N. Ganev, A.K. Srivastava, A. Nag, A.R. Dixit, S. Tiwari, J. Scucka, M. Zelenak, S. Hloch, P. Hlavacek, Surface integrity in tangential turning of hybrid MMC A359/B4C/Al2O3by abrasive waterjet, J. Manuf. Process. 28 (2017) 11–20.
[19] M. Lieblich, S. Barriuso, J. Ibanez, L. Ruiz-de-Lara, M. Diaz, J.L. Ocana, A. Alberdi, C. Gonzalez, On the fatigue behavior of medical Ti6Al4V roughened by grit blasting and abrasiveless waterjet peening, J. Mech. Behav. Biomed. Mater. 63 (2016) 390–398.
[20] A. Azhari, C. Schindler, C. Godard, J. Gibmeier, E. Kerscher, Effect of multiple passes treatment in waterjet peening on fatigue performance, Appl. Surf. Sci. 388 ((2016) 468–474.
[21] A. Azhari, C. Schindler, K. Hilbert, C. Godard, E. Kerscher, Influence of waterjet peening and smoothing on the material surface and properties of stainless steel 304, Surf. Coat. Technol. 258 (2014) 1176–1782.
[22] A. Naito, O. Takakuwa, H. Soyama, Development of peening technique using recirculating shot accelerated by water jet, Mater. Sci. Technol. 28 (2012) 234–239.
[23] J. Xie, D. Rittel, A two-dimensional model for metallic surface roughness resulting from pure waterjet peening, Int. J. Eng. Sci. 120 (2017) 189–198.
[24] T. Abhishek, S.G. Amrinder, R.M. Seetha, Q. Dong, K.V. Vijay, Effect of Temperature on Microstructure and Residual Stresses Induced by Surface Treatments in Inconel 718 SPF, 344 (2018), pp. 93–101.
[25] P.K. Farayibi, T.E. Abioye, J.W. Murray, P.K. Kinnell, A.T. Clare, Surface improvement of laser clad Ti-6Al-4V using plain waterjet and pulsed electron beam irradiation, J. Mater. Process. Technol. 218 (2015) 1–11.
[26] S. Barriuso, M. Lieblich, M. Multigner, I. Etxeberria, A. Alberdi, J.L. Gonz Alez-Carrasco, Roughening of metallic biomaterials by abrasiveless waterjet peening: characterization and viability, Wear 270 (2011) 634–639.
[27] M. Ijiri, D. Shimonishi, D. Nakagawa, T. Yoshimura, Evolution of microstructure from the surface to the interior of Cr-Mo steel by water jet peening, Mater. Sci. Appl. 8 (2017) 708–715.
[28] A.K. Srivastava, A. Nag, A.R. Dixit, S. Tiwari, J. Scucka, M. Zelenak, S. Hloch, P. Hlavacek, Surface integrity in tangential turning of hybrid MMC A359/B4C/Al2O3by abrasive waterjet, J. Manuf. Process. 28 (2017) 11–20.
[29] M. Sedlacek, P. Gregorcic, Bojan Podgornik, Use of the roughness parameters Ssk and Sku to control friction—a method for designing surface texturing, Tribol. Trans. 60 (2017) 260–266.
[30] J. Xie, D. Rittel, The effects of waterjet peening on a random-topography metallic implant surface, Eur. J. Mech. A Solids 71 (2018) 235–244.