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ORIGINAL ARTICLE

Mechanical characterisation of water-jet shot peened H13 tool steel surface

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ABSTRACT – A wear-resistant surface is achievable via the surface treatment of various sources such as laser, water-jet, ion beam, and plasma. This paper investigates the parameters of water-jet shot-peened H13 tool steel for minimum surface roughness and maximum hardness properties. Water jet processing parameters are significant in determining the surface roughness as well as hardness properties. Water-jet shot-peened (WJSP) was used in this experiment to improve the surface properties of H13 tool steel. The parameters are pressure and feed rate of 172 MPa to 310 MPa and 2600 mm/min to 10000 mm/min. The shot-peened samples were characterised for surface topography, surface roughness, and hardness properties. A laser confocal microscope was used to determine the dimension of the modified surface from shot peening and average surface roughness. Hardness properties were measured using the Vickers scale. From topography analysis, the surface roughness reading on the shot-peened surface was measured as much as 6.88 µm to 14.06 µm. Minimum surface roughness measured was 6.88 µm on sample processed at pressure and feed rate 172 MPa and 2600 mm/min. The hardness properties of the shot-peened subsurface were between 196 HV and 227 HV. The resulted hardness properties were due to plastic deformation from abrasive particle bombardment during shot peening. The findings are important to designing enhanced surface properties for mould and die applications.

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INTRODUCTION

In surface processing, ultra-high-pressure water-jet (WJ) has gained popularity. Surface preparation refers to any process used to improve or remove the surface exposed to a component or structure [1]. Water-jet technology of high pressure has been studied for many decades [2-4]. Many applications involve water-jet processing, such as machining, surface preparation, cleaning, coating removal, surface treatment, and shot peening [5,6]. Other than that, in water-jet technology, pure water-jet (WJ) and abrasive water-jet (AWJ) are commonly applied in the automotive and aerospace industries [7,8]. In the automotive manufacturing industry, forming process requires a wear-resistant die surface to produce components at a mass scale [9]. The die surface tends to fail when upper die teethes, which makes up the mould component part of the industrial punching machine [10]. This is important in the production line to ensure that the material produced can be used effectively [11].

Water Jet Peening (WJP) and Water Jet Shot Peening (WJSP) are new applications in water jet technology. WJP come from pure water-jet, which uses high-pressure water direct to the surface component that tends to cause plastic deformation [12]. WJP gives advantages to improving the fatigue strength and resistance to corrosion [13]. The other researcher said the mechanical surface strengthening was produced by the high impact of water on the metal surface. It causes plastic deformation that forms high compressive residual stress on the surface near the layer [14]. Meanwhile, WJSP is the same as AWJ, which uses a high-pressure water jet with an additional abrasive particle. Based on previous works, WJSP or AWJ process has been used on stainless steel, aluminium alloy 5005 and carbon steel 1045 to improve the surface properties in engineering components. The surface roughness shown for stainless steel, aluminium alloy and carbon steel is 1.37 µm, 4.23 µm and 1.53 µm, respectively [15]. The depth of the water jet shot-peened layer ranged between 4.15 µm and 12.38 µm [16]. Although many materials have been investigated, there is still a lack of water jet shot peening on tool steel. In industrial applications, most researchers studied water jet shot peening processing on aluminium alloy [17]. On the other hand, tool steel surface modification has been reported for different processing methods such as laser surface melting and laser cladding [18-20]. This work aims to produce minimum surface roughness, and maximum hardness properties using water jet shot peeing. Metallographic study and 3D topography analysis were conducted to generate a detailed profile of water jet shot-peened surface at different parameters.

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METHODS AND MATERIALS

Materials

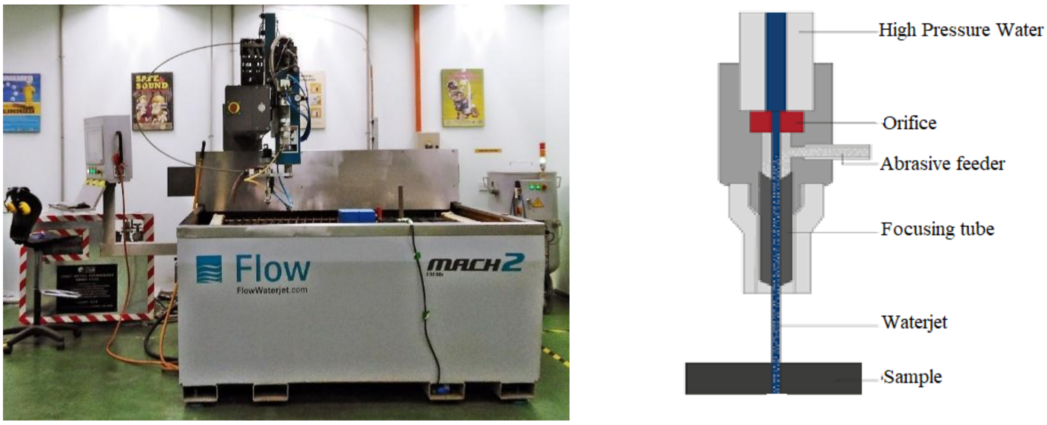
The material used in this experiment was ASSAB 8407, which is equivalent to AISI H13 tool steel, where it functions in hot and cold work tooling applications. H13 tool steel is known for its high surface quality, high hardenability, and toughness [21]. Therefore, it qualifies H13 tool steel to be used for die application. Table 1 shows the chemical composition of H13 tool steel. The test plate used for this experiment has a dimension of 31.2 × 68.45 mm in surface area and 7.45 mm thickness. The surface plate needs grinding and polishing before conducting the process and experimentation.

Table 1. Chemical composition (wt%) of AISI H13 tool steel

Element (wt%)				
C	**Si**	**Mn**	**S**	**Cr**
0.401-0.473	0.968-1.000	0.327-0.343	0.0055-0.0069	4.92-5.00
Mo	**Ni**	**Al**	**Co**	**Cu**
1.17-1.24	0.073-0.107	0.024-0.046	0.0199-0.0207	0.08-0.165
Ti	**V**	**W**	**Nb**	**Fe**
0.0094-0.0123	0.901-0.165	0.0252-0.0399	0.003	Balance

Water Jet Shot Peening Process

Water jet shot-peened (WJSP) tests were carried out on M2-1313B Flow Mach 2 abrasive water jet machining, as in Figure 1(a). This machine uses a direct drive pump with a maximum pressure water jet of 55,000 psi and a low traverse speed from 0.01mm/min to 5000 mm/min. Garnet was selected as an abrasive particle with 80 mesh in abrasive size. The process was run by a high-pressure water jet mixed with abrasive particles that shot on surface H13 tool steel with different parameters. Each sample was clamped on the machine table and run the experiment. In this experiment, the manipulated variables are pressure and feed rate, while the standoff distance (SOD) is constant. The parameter for this experiment is given in Table 2, with constant SOD of 38 mm. The parameter is based on six samples at three different pressures of 172, 241 and 310 MPa, while the feed rate ranges between 2600 and 10000 mm/min. Water jet shot peening is the process of high-pressure water-jet and added abrasive particles to generate the required surface plastic deformation. This experiment used the standard abrasive water-jet that is widely used in the industry. This experimental set up is given in the schematic diagram of Figure 1(b).



(a) (b)

Figure 1. (a) M2-1313B abrasive water jet machine, and (b) Schematic drawing of WJSP

Table 2. Parameter of water jet shot-peened

Sample	Pressure, p/ (mpa)	Feed rate, s (mm/min)
1	172	3000
2	172	2600
3	241	7000
4	241	6000
5	310	10000
6	310	9400

Sample Preparation

Samples were prepared for topography and hardness characterisation after the water-jet shot-peening process. The samples were cut using a precision cut-off machine and prepared for microscopy analysis using an automatic mounting press machine. Then the mounted samples were ground and polished using respective grind papers and polished using three different polishing cloths; silk cloth, red felt cloth and imperial cloth [22]. After that, chemical etching was conducted using a 2% nital solution to enhance the grain structure.

3D Topography Characterisation

The surface topography and roughness were measured using LEXT OLS5000 3D Measuring Laser Microscope. The measurements were averaged from at least three readings to determine the surface roughness, Ra. This is to minimise the variability of surface finish. The 3D topography was captured for the detailed morphology of the shot-peened surface. Micrographs of shot-peened cross-sections were captured using IM700 Series Inverted Optical microscope.

Hardness Properties Characterization

Hardness properties characterisation was conducted using a Vickers hardness tester with 0.1 kgf force and a loading time of 10 s. The Vickers hardness tester is integrated with the hardness analysis software. In this test, an average of seven measurements was recorded at every trench profile for each sample by referring to previous researchers [23]. The indentations were measured at distances of at least 25 µm from each other. Hardness measurement on the sample cross-sections is depicted by the micrograph.

RESULTS AND DISCUSSION

Topography Analysis

The micrographs in Figure 2 shows the cross-section of water jet shot peening based on the parameters given in Table 2. These micrographs in Figure 2 shows the engraved effect due to water jet parameters, where increased engraved depth occurs at the lower feed rate of constant pressure. Using 172 MPa pressure, engraved surface depth is shallow at 3000 mm/min compared to 2600 mm/min. The engrave depth at 3000 mm/min is 141.06 µm, whereas the 2600 mm/min sample produces 157.72 µm depth. The difference in depth between these two is 15.66µm. Meanwhile, the length of the engraved surface increases to 6.39 µm from 1198.49 µm to 1205.13 µm

A similar observation is shown in micrographs 2(c) and 2(d), where more material was removed from the surface when shot peened at 6000 mm/min and 7000mm/min. The maximum engraved depth of 140.33 µm has resulted from the shot-peened sample at 241 MPa pressure and 7000 mm/min feed rate. Then for a 6000 mm/min feed rate, the engraving depth is 132.49µm. Therefore, the engraving depth difference is 7.84 µm which is the smallest between maximum and minimum pressure. In micrographs 2(e) and 2(f), more material removal is observed from the surface when shot peened at 9400 mm/min and 10000 mm/min. The maximum engraved depth of 168.13 µm resulted from the shot-peened sample at 310 MPa pressure and the maximum 10000 mm/min feed rate. Then at 9400 mm/min feed rate, the engraved depth is 159.58 µm. Therefore, the difference in engraving depth is 8.55 µm.

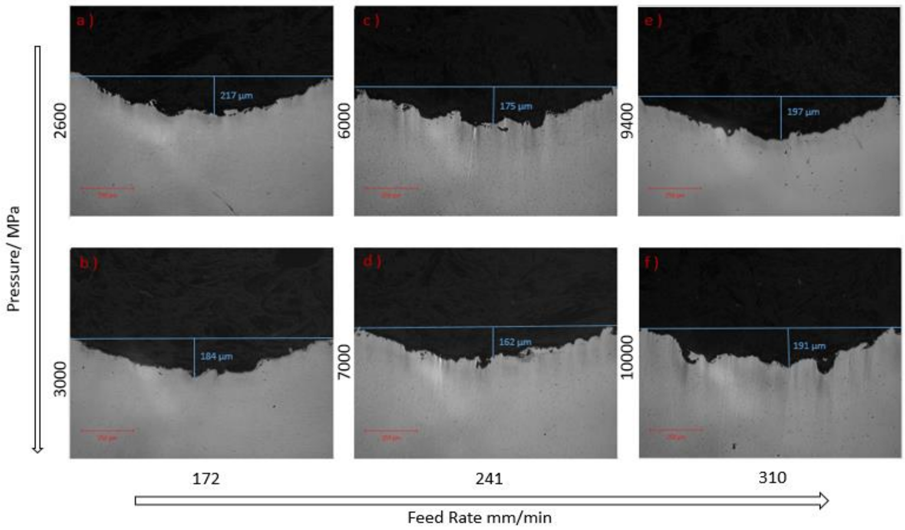


Figure 2. Micrographs of water jet shot peening AISI H13 tool steel on (a) Sample 2, (b) Sample 1, (c) Sample 3, (d) Sample 4, (e) Sample 6 and (f) Sample 5

Figure 3 shows the cross-sections of engraved surfaces responding to pressure and feed rate variation in water jet shot peening of H13 tool steel at constant SOD of 38 mm to produce different engraved depths. From the parameters in Table 2, the graph is plotted at three levels of setting; low, medium and high. At a pressure setting of 172 MPa, two samples were processed, with a maximum and minimum feed rate of 3000 mm/min and 2600 mm/min. At a pressure of 241 MPa, the maximum and minimum feed rate is 7000 mm/min and 6000 mm/min. Whereas the highest pressure of 310 MPa was conducted on samples at 10000 mm/min and 9400 mm/min feed rate. The surface roughness responding to the parameters is given in Figure 4 and 5.

At higher feed rates and pressure settings, the surface roughness ranges between 11.39 and 14.06 µm, while the lower settings reduced the surface roughness to 6.878 µm. This is in agreement with previous work, where increasing the pressure by 50 MPa increased the surface roughness twice. Higher pressure increased surface roughness due to abrasive particles impingement on the surface. However, at 310 MPa pressure, the water flow bombardment on the surface overcame the impact of the abrasive particles compared to the surface peened at 241 MPa pressure. Additionally, the high water pressure reduced residual stress formation significantly [24]. Meanwhile, increasing feed rate at a constant water pressure increased surface roughness. A higher feed rate makes the surface of steel become more eroded, and the abrasive particles separate. Consistent with findings in ref. [13] the lower feed rate range of 1000-3000 mm/min effect on surface roughness properties indicated a similar trend.

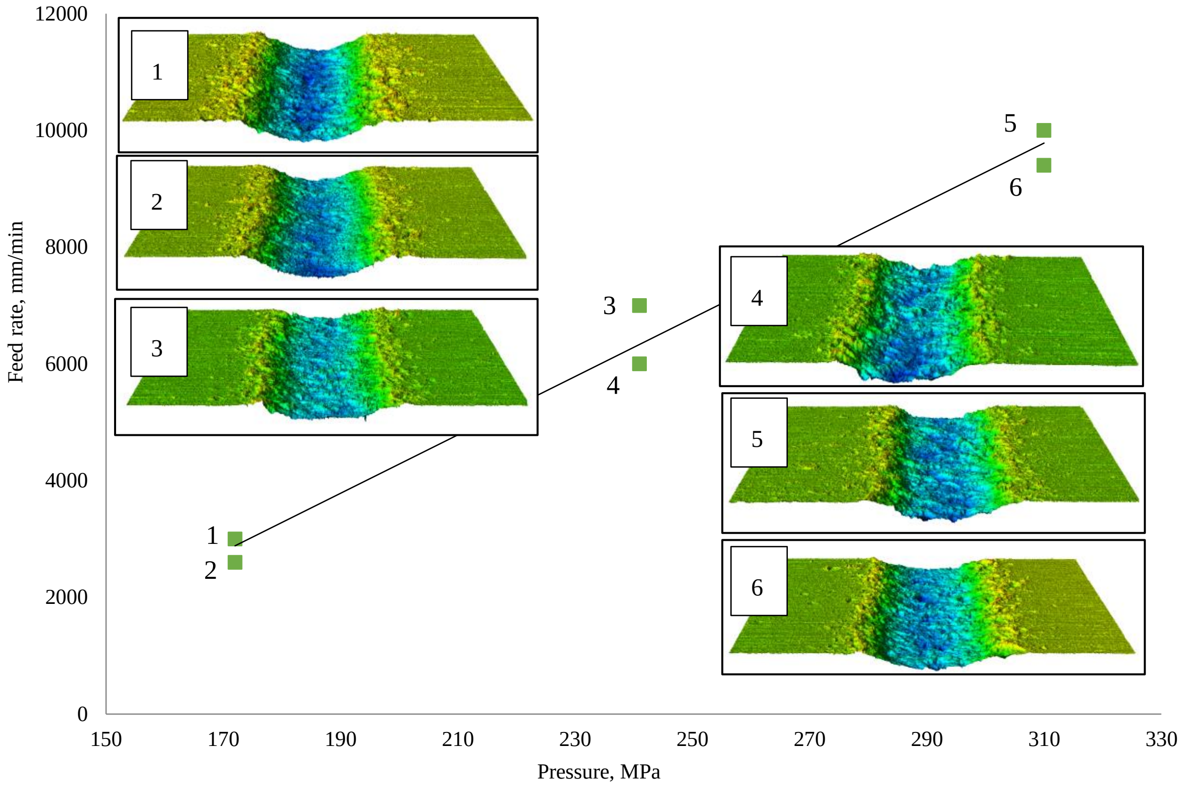


Figure 3. Graph pressure and feed rate mapping for water jet shot peening of H13 tool steel at constant SOD of 38 mm

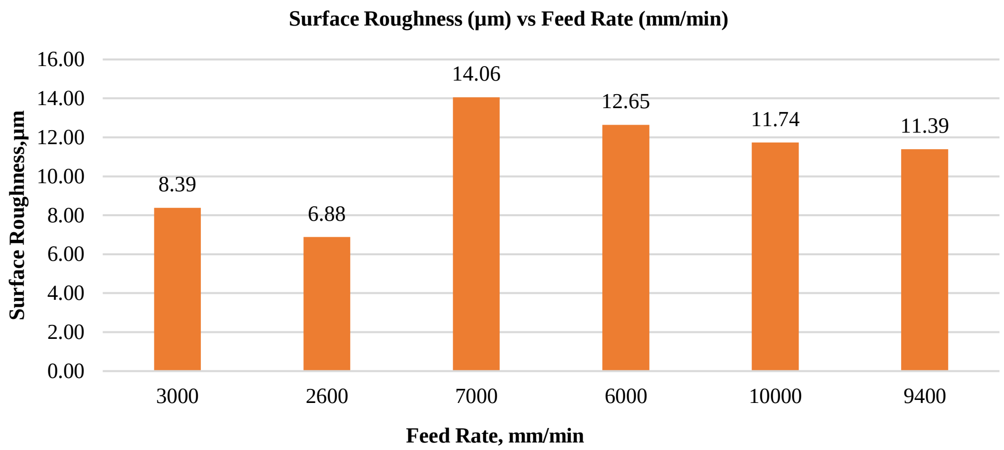


Figure 4. Graph surface roughness against feed rate

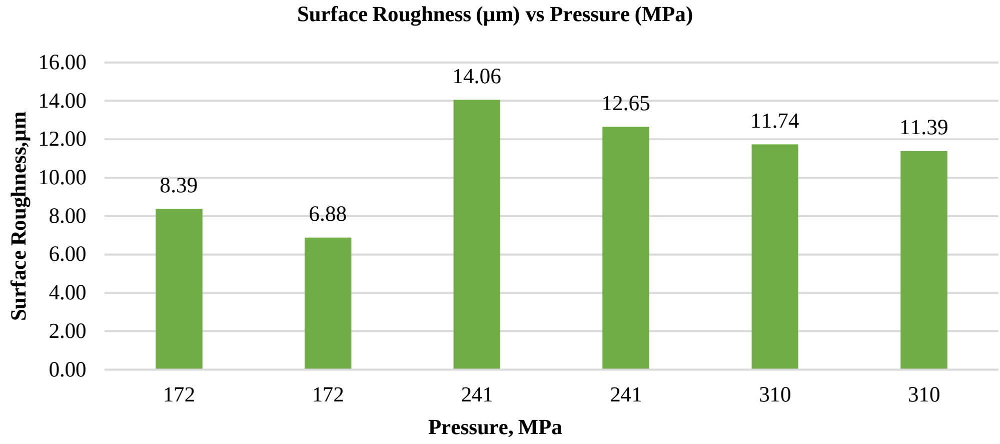


Figure 5. Graph surface roughness against pressure

Based on the different parameters, the micrograph shows different engrave depths that can be seen clearly, like trench shape due to abrasive particles that bombarded the H13 tool steel surface. At lower pressure of 172 MPa and a lower feed rate of 2600 mm/min, the surface is more eroded compared to the high feed rate. This is because the particles of abrasive that strike the sample lose their sharpness, and some of the abrasive particles penetrate the surface while the others retarded toward the top surface. Moreover, the depth at a lower feed rate decreases compared to the higher feed rate at low pressure. For high pressure of 310Mpa, the high feed rate is not affected more than the lower feed rate because the abrasive particles are continuously shot on the surface. The engraved surface dimensions are plotted in Figure 6.

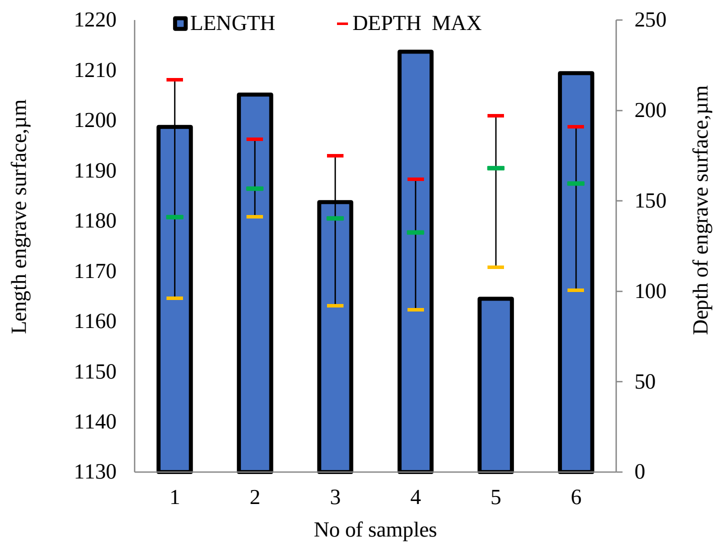


Figure 6. Dimension of the engraved surface from water-jet shot-peening of H13 tool steel

Hardness Properties

The hardness properties of the water-jet shot-peened H13 tool steel subsurface are plotted in Figure 7. The graph shows maximum, minimum and average hardness for six samples. From the hardness measurement, the hardness properties of the H13 tool steel subsurface after shot-peened ranged between 164 HV and 218 HV. The minimum hardness of 194 HV is in sample 3, which was shot-peened at a feed rate of 7000 mm/min and pressure of 241 Mpa. Then, the maximum hardness is 218 HV from sample 6 at a feed rate of 9400 mm/min and the highest pressure of 310 MPa. The hardness increase is higher at the higher feed rate in comparison to the pressure changes.

Therefore, at 310 MPa pressure and feed rate of 9400 mm/min, produced maximum hardness while shot-peened sample at the medium pressure of 241 MPa and feed rate of 7000mm/min exhibits the minimum hardness for this experiment. The higher hardness in sample 6 is due to the high compressive residual stress due to the abrasive particles that bombarded the H13 tool steel surface. Thus, variation of pressure and feed rate of water-jet processing caused plastic deformation on the H13 tool steel subsurface [2]. The hardness properties increased after shot peening is caused by compression force resulting from high-pressure water stream and with added abrasive particles that make the energy transfer to the surface samples. However, the lower water pressures may result in less abrasive particle bombardment on the H13 steel surface than the higher water pressure due to a weaker flow rate, which is significant to surface roughness findings. Thus, excessive or insufficient pressures caused lower compressive residual stress on the surface [24]. In previous research, the hardness properties of water jet shot-peened for Nickel surface ranged from 120 HV to 186 HV [25], while stainless steel was 192 HV [26].

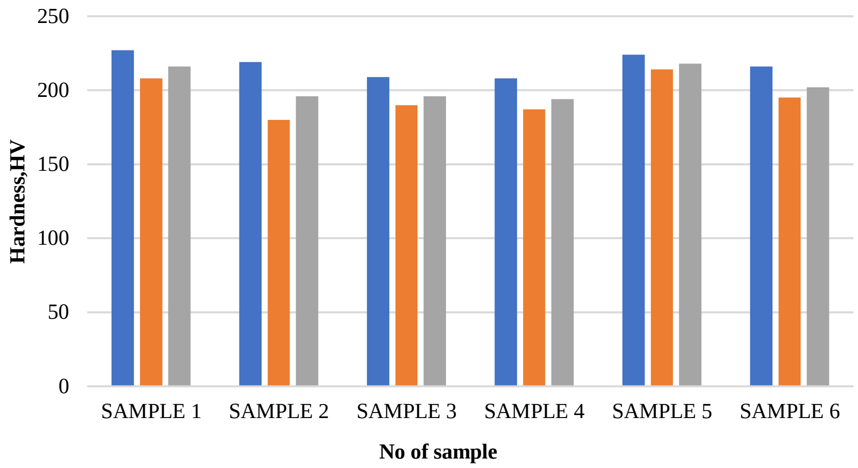


Figure 7. Hardness properties of water-jet shot peened H13 tool steel subsurface

CONCLUSION

In this paper, WJSP treatment used H13 tool steel, which is still lacking in water jet shot peening. At constant abrasive flow, both pressure and feed rate affected surface roughness, erosion and hardness properties of WJSP H13 tool steel. The highest hardness of 227 HV was measured at 310 MPa water pressure and 9400 mm/min feed rate, while the surface roughness was at a minimum of 6.88 µm when pressure and feed rate was at the lowest (172 Mpa, 2600 mm/min). These findings are significant to designing water jet shot peening of tool steel for enhanced mechanical properties.

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