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Original scientific paper

Strengthening Effect after Disintegration of Stainless Steel Using Pulsating Water Jet

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Abstract: The article deals with the measurement of micro-hardness of the track by the action of ultrasonic excitation of pulsating water jet. The cumulative effect of liquid matter in the form of droplets concentrated in waveform measurements was provided in horizontal and vertical direction to material core (AISI 304). The material was subjected to pressures of p = 40, 50 and 60 MPa with the actuator working at a frequency of 20,14 kHz and traverse speed v = 1,1 mm/s, v = 0,80 mm/s and v = 0,30 mm/s respectively. The micro hardness measurement was carried out after machining it by pulsating water jet. The values were recorded in the zone located transversally under the trace to the depth of 1,5 mm with 0,1 mm distance between successive points. It was found that the deformation of material was ascertained from the boundary to the outer environment created by pulsating water jet to the inner core of the material. The results indicate that the pressure was the most influential parameter, which was responsible for the deformation strengthening of the material.

Keywords: deformation; microhardness; pulsating water jet

1 INTRODUCTION

Over the years WJ´s are used for different machining processes such as cutting [1, 2], drilling [3], milling [4-6], turning [7] and surface treatment [8]. The mechanical energy of the liquid creates the basis of water jet technology. Owing to the requirements for generating jets for specific application, till today the water jet technology has undergone various technological modifications like abrasive water jet (AWJ), abrasive suspension jet (ASJ) [9] and pulsating water jet (PWJ) [10]. Still, the destructive impact of water in the form of droplets, continual flow and waves on various solid materials is not a very well understood physical phenomenon. The application of kinetic energy of the focused liquid stream on a solid material causes the disintegration and thus removal of the material. This liquid impact on a solid surface occurs in two stages. In the first stage, liquid behaves in a compressible manner and generates water hammer pressure, which is responsible for the major damage caused during the impact. As this pressure releases the second stage commences in which the liquid flows away from the point of impact moving at a velocity five times the impact velocity. Hence, an additional shear force acts across the surface in addition to the normal forces [11]. During disintegration by means of pulsating water jet the high velocity liquid mass collides with the solid which produces short high pressure transients which is responsible for the damage on the surface and inside the material [12]. With PWJ, the effectiveness of the jet is increased by the generation of individual clusters, which subsequently impinges the surface of the material with high kinetic energy each time when the pulses strike the surface. In the recent years, PWJ technology was applied to different fields of applications. Foldyna et al [13] utilized the technology for the erosion of metals where the influence of the pulsed water jet impacts on the erosion of the surface of the metals was investigated. It was observed that the erosion occurred in three stages: initial plastic deformation, creation of erosion pits, pits merging to form erosion crater. Lehocka et al. [14] used PWJ for disintegrating Copper alloys and investigated the surface topography, morphology and anisotropy of the copper alloys. The average values of the surface roughness were compared with the mechanical properties for each groove made under different sets of parameters for assessing the required microgeometry and purity of surfaces. In the medical field Hloch et al. [15] investigated the disintegration of bone cement by PWJ. The depth of penetration was measured using optical profilometer and it was concluded that this technology is effective for reimplantation of cemented endoprosthesis without causing heat and mechanical damage to the surrounding tissue [16]. PWJ has also been used for disintegrating rock materials [17, 18]. Sitek et al., [19, 20] used PWJ technology for removal of concrete in repair of concrete structures. The effect of continuous and PWJ on concrete surface was compared using optical microscope and image analysis and it was observed that PWJ has shown higher performance than continuous WJ when operated under the same conditions. Descaling of the surfaces is another application in which PWJ technology was employed. Hnizdil et al. [21] performed descaling on carbon steel and steel sheets and observed that the scale layer was thinner when descaling was performed using PWJ than that performed using continuous WJ.

Presently, WJ and AWJ are widely being used in the industries for different applications, but these technologies have certain technological and economic limitations. These limitations can be overcome by adopting a means to cause erosion at lower pressure, which can be achieved by using PWJ technology [14]. The effect of pulses during the impingement of water jet on the solid surface has not been explored much until date. However, a few studies have been reported regarding the effect of impact of pulsed water jet with the solid surface [22] but still this area needs to be studied in a broader way in order to utilize this technology beneficially from the economical point of view.

The present work aims at studying the effect after impinging the surface of stainless (AISI 304) steel by pulsating water jet. In order to study the strengthening effect microhardness measurements were conducted on the disintegrated stainless steel samples in the zone located transversally under the trace.

2 EXPERIMENTAL SET UP

The experiment was carried out in cooperation of the Faculty of Manufacturing Technologies in Prešov and the Institute of Geonics of CAS, v.v.i. in Ostrava, which has the technological assembly for the disintegration of materials using pulsating water jet generated by ultrasound. The principle of generating pulses in this type of assembly is based on the generation of vibrations using an ultrasonic converter. The vibrations are transmitted to water in a nozzle using a waveguide and ultrasonic tool. The water jet exits the nozzle in a continuous form and after a certain length its starts forming into individual clusters of liquid. The material is subsequently disintegrated by shock impacts of water clusters with high kinetic energy. The technological assembly used in the experimentation consisted of the 2D table, cutting head (Fig. 1a), fixture specially designed for this experiment, StoneAge circular nozzles of required equivalent diameter, Hammelmann HDP 253 hydraulic high-pressure pump (max. operating pressure of 160 MPa, maximum flow rate of 67 l/min), Ecoson WJ-UG_630-40 ultrasonic device used for the generation of pulses and ABB IRB 6640 - 180//2.5 robot intended for handling the cutting head. The technological conditions of the device in this experiment were as follows: frequency f = 20,14 kHz, power output P = 250 W, length of resonant chamber l_{rk} [mm] adjusted manually using a nut. Standoff distance of nozzle from material z (mm) was adjusted depending on frequency f (kHz) and power output P (W). Nominal values under which the tests were conducted are listed in Tab. 1. Material from AISI 304 steel was used for the experiments. This is an austenitic stainless chromium-nickel steel with good cold workability that is resistant to water, steam, moisture, and weak acids. Tabs. 2 and 3 describe the basic values and chemical composition of the material as specified by the manufacturer. For the experiments, three types of samples were prepared from the same material, while each material was machined with different working parameters (traverse speed v (mm/s), pressure of water jet p (MPa) and stand of distance of nozzle z (mm)).

Table 1 Nominal values used in machining of samples

Sample	p / MPa	d / "	v / mm/s	z / mm	l_{rk} / mm
1	40	0,042	1,1	30	24
2	50	0,052	0,8	50	21
3	60	0,063	0,5	60	

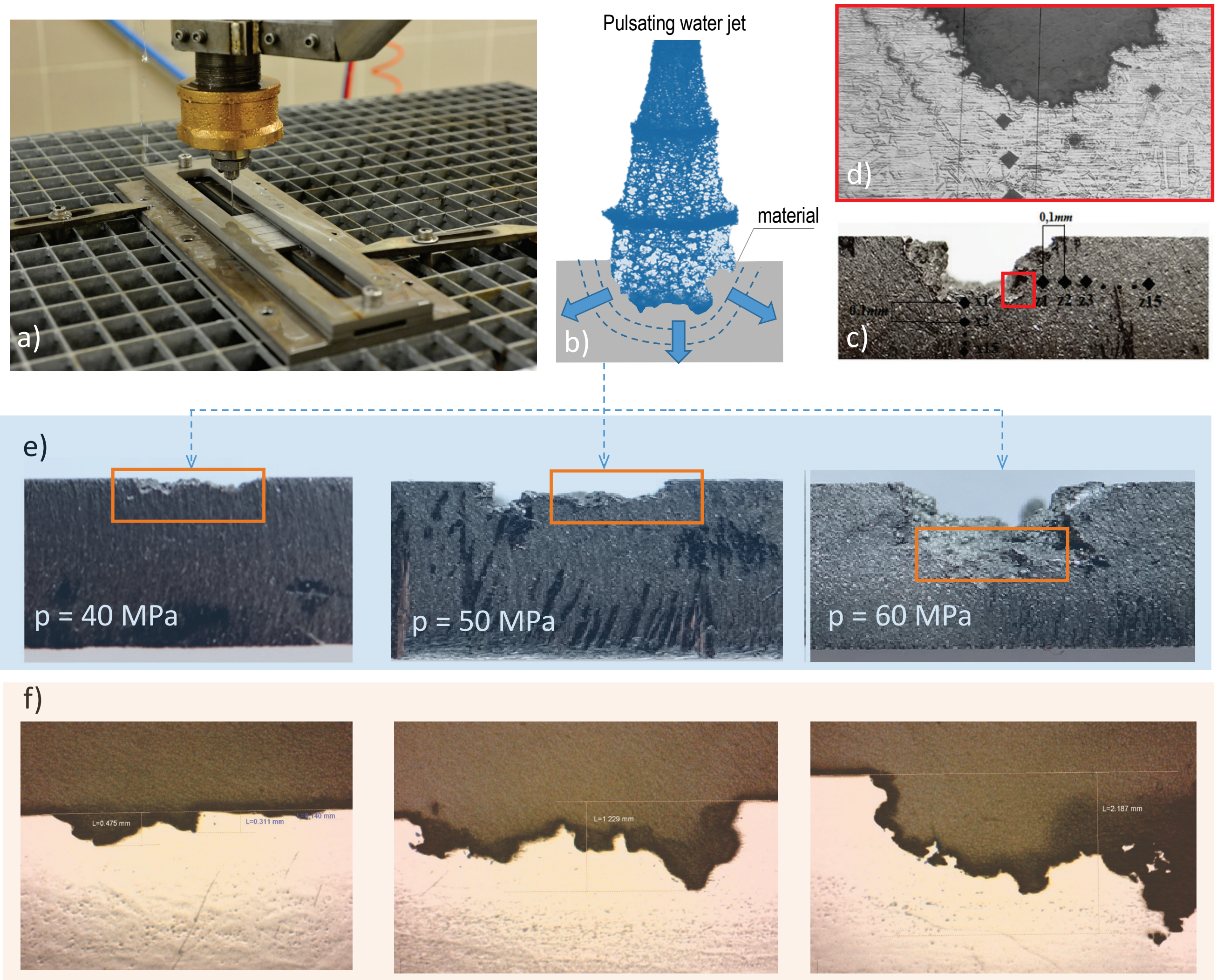

Figure 1 Experimental setup and measurement a) PWJ cutting head and samples, b) principle of PWJ disintegration, c) measurement method, d) austenitic structure of the AISI 304 material, e) traces on AISI created under p = 40, 50 and 60 MPa, f) photographs of polished sections

The grinding and polishing of samples for the purpose of observation under microscope was carried out using the KOMPAKT 1031 device from MTH Hrazdil s.r.o., grinding SiC papers with different thickness and grain size, polishing cloth, emulsion on the base of Al_2O_3 + H_2O w, commercial marking AP-A POWDER, 5µm from Struers were used. The samples intended for observation under the microscope were etched using the prepared etching agent from Struers with Adler make, thinned with 2% HNO_3 and ethyl alcohol.

Microhardness tester of CV 400 DAT type, from CV Instruments Company, with digitalized mechanized head was used for measuring microhardness. Each of the samples was gradually prepared and measured using the same method of measurement, Figs. 1c and 1d where measurement took place from the beginning of the action of pulsating water jet towards the centre of material with an interval of 0,1 mm in regular distances after each 15 measurements, in the *x* and *z* planes, respectively. Load time was 10 seconds and load weight 200 g. The samples were prepared using standard metallographic techniques [23] by grinding, polishing, and etching. Thermally unaffected zone at the point of cut is one of the advantageous factors of cutting material by water jet. Because the point of material cutting is not exposed to high temperatures, as in the case of other cutting methods, for example: laser or plasma, the transformation of the material structure by the effect of high temperatures does not occur. Also, the pressure caused by the impingement of water jet on the material surface did not cause the transformation of the structure in any of the sample. Intact grain of austenite can be observed in the sample 2 that is from AISI 304 steel like other samples. We can observe areas that were only minimally deformed, and that were manifested by increased values of microhardness in the initial zone after the use of pulsating water jet technology.

3 RESULTS AND DISCUSSION

From the measurements, it is apparent that the pressure is the most influential factor that was responsible for the material disintegration under the aforementioned parameters (Tab. 1). The change of traverse speed was carried out in order to achieve the maximum disintegration effect. The higher working pressure and smaller nozzle diameter caused the larger material removal, which is also visible on the samples used (Fig. 1e). The arithmetic average values were calculated for individual samples from measurements that were not affected by deformation Figs. 2-4 (green line). These were subsequently compared with the individual measured values of samples that were measured at the point of largest deformation strengthening. The course of material microhardness is graphically depicted. The measured value of microhardness HV at load of 200 g is depicted on axis *x*. Distances of individual indents of diamond body into material in mm are depicted on axis *x*.

Table 2 The chemical composition of AISI 304

STN	W. Nr.	AISI	C	P	S	Si	Mn	Cr	Ni	N
17,240	1,4301	304	0,03	0,045	0,03	1,00	2,00	17-20	8-10,5	0,11

Table 3 Mechanical properties of AISI 304

STN	W. Nr.	AISI	Tensile strength R_m / MPa	Yield strength		Elongation / %	HRB_{max}	Structure
				$R_{p0,2}$	R_{p1}			
17,240	1,4301	304	500/900	175	210	45	88	austenitic

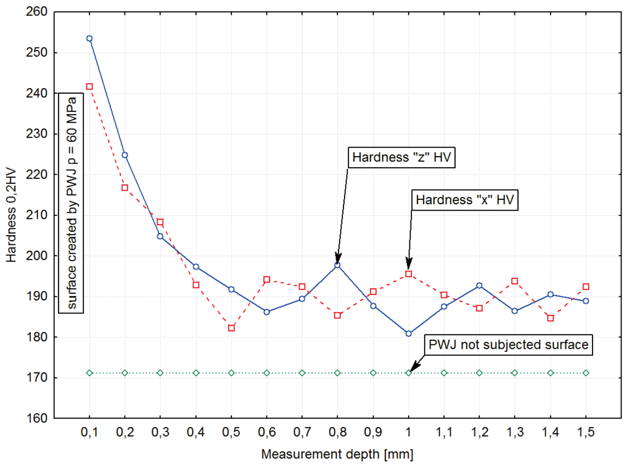

Figure 2 Hardness measurement of sample 1 (Tab. 1) using nominal parameters: p = 40 MPa, v = 1,10 mm/s, d = 0,042" (d = 1,067 mm)

The microhardness results of the sample machined under the above conditions show that the maximum value of microhardness in the zone of deformation strengthening is 226,4 HV at measurement point z, and 235,3 HV at measurement point x at load of 200 g (Fig. 2). The average value of microhardness from these measurements is 230,8 HV and the average value of microhardness out of the deformation zone of the material is 168,3 HV. From the aforementioned data it follows that the difference in microhardness between both zones of material is 62,5 HV. It is clear from the results that lower pressure caused by the impact of water jet on material influences the degree of material deformation strengthening. Other nominal parameters influencing the degree of deformation strengthening of material hardness are: nozzle feed rate and nozzle diameter, whilst the pressure of liquid jet has the maximum impact on deformation of microhardness. It follows from the aforementioned chart (Fig. 2) that the magnitude of the nominal values for this sample did not cause larger deviations in microhardness in the deformation zone in the case of individual indents. The curve has a stable direction in the case of the last indents, i.e. in measurements that were carried out farthest from the point of machining using PWJ. On measuring the hardness of the sample machined under the above condition it was observed that the maximum measured value in the area of deformation strengthening was 237,30 HV at point *z*, and 234,7 HV at point *x* at load of 200 g. The average value was 236 HV and the average value of microhardness measured out of the deformation zone of material was 170,9 HV.

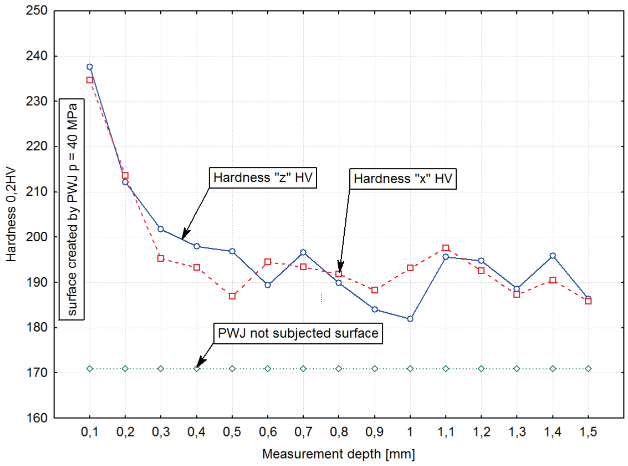

Figure 3 Hardness measurement of sample 2 (Tab. 1) using nominal parameters: p = 50 MPa, v = 0,80 mm/s, d = 0,052" (d = 1,067 mm)

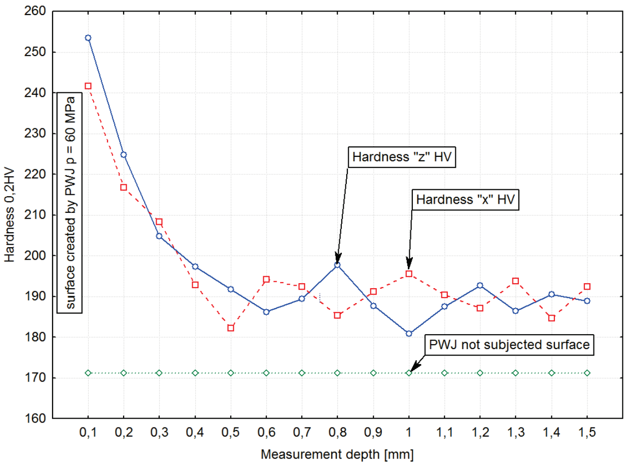

Figure 4 Hardness measurement of sample 3 (Tab. 1) using nominal parameters: p = 60 MPa, v = 0,30 mm/s, d = 0,063" (d = 1,6 mm)

The maximum difference of microhardness between both zones is 65,1 HV. It follows from the aforementioned ascertainment that higher pressure of PWJ and change in diameter and feed of nozzle results in the increase of deformation material strengthening. The higher pressure of water jet, which is a bearer of large kinetic energy, is the main factor responsible for the increase of deformation strengthening. It can be deduced from the chart that larger microhardness of material exists in the deformation zone up to indent 3, i.e. up to 0,3 mm from the point of cut. Beyond this distance, the curve starts to decrease and acquires values that approximately equal the values measured out of the deformation zone.

In the third case, the microhardness was conducted on the affected zone of machined material at different nominal parameters of PWJ than the previous two samples (Fig. 4). It was observed that the highest recorded value of microhardness in the area of deformation strengthening at the measurement point z was 253,50 HV and at point x 241,6 HV at a load of 200 g. The average value of material microhardness calculated from these values was 247,5 HV and the average value of material microhardness out of the deformation strengthening zone was 171,2 HV. The maximum difference of values in both zones was 76,3 HV. The higher pressure of water jet that impinged on the point of machining caused higher values of deformation strengthening than in the case of the previous sample. Nozzle diameter and nozzle feed were primary effects causing deformation strengthening. It can be deduced from the chart that larger microhardness of material exists in the deformation zone up to indent 3, i.e. up to 0,3 mm from the point of cut. Beyond this point, the curve starts to decrease and acquires values that approximately equal the values measured out of the deformation zone.

4 CONCLUSIONS

The values of microhardness deformations formed due to the strengthening of the material by the effect of higher pressures of pulsating water jet machined at different rates and diameters of nozzles. This non-conventional technology using discontinuous water jet has been the object of a large quantity of research papers to date, and it is continuously developing. This paper solves issues of the origin of deformation depending on the change of material microhardness by pulsating water jet. The experiment was carried out on three samples of the same material AISI 304, while each sample was machined using different nominal parameters. The measurements and their evaluation highlight that nominal parameters such as nozzle diameter, nozzle feed and above all magnitude of water jet pressure have a direct influence on material deformation strengthening in the area of cut. Sample 1 that showed the minimum values of material microhardness was machined using the lowest pressure of water jet that caused the lowest deformation strengthening of material. A higher value of material microhardness was measured in sample 2, causing higher material deformation in the machining area. This fact was affected by the higher pressure of water jet, and at the same time by larger nozzle diameter, whilst nozzle feed was slower than in the previous case. The highest pressure of water jet was used in the case of sample 3, with the largest nozzle diameter and the slowest nozzle feed of all nominal parameters used in this study. These nominal parameters influenced the material microhardnes which was maximum as compared to the values recorded for other samples.

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