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Surface integrity evaluation of brass CW614N after impact of acoustically excited pulsating water jet

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Abstract

Presented article is focused on surface integrity evaluation of brass CW614N form the sight of surface topography, structural changes in surface layers and strengthening character in subsurface layers after impact of acoustically excited pulsating water jet (PWJ). Surface topography was evaluated using optical profilometry. Structural changes in subsurface layer were observed based on mass material removal Δm [mg/s] and maximal depth of penetrance of PWJ h_{max} [mm]. Nano indentation measurement according to Berkovich were used to examination of strengthening character in subsurface layer. Disintegration of experimental samples was performed under constant technological conditions: hydraulic power of plunger pump P_h = 19 kW; round nozzle diameter d = 1.6 mm; feed speed rate v = 0.75 mm/s; pressure of plunger pump p = 38 MPa, stand-off distance of nozzle from target material z = 45 mm; ultrasound frequency f = 20.29 kHz and as variable factor was set power of ultrasound P on values 340, 360 and 380 W. In terms of surface topography experimental investigation proved that PWJ under selected conditions is not suitable for precision machining. Evaluation of the surface characteristics indicates that the chemical composition has a significant effect on material weight loss Δm [mg/s] and a maximum depth of penetration of PWJ h_{max} [mm]. Evaluation of characteristics of subsurface layer was observed strengthened area with lower elasticity.

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Keywords: Pulsating water jet; surface integrity; mass material removal; brass; nanoindentation

Nomenclature

AWJ	abrasive water jet
PWJ	Pulsating Water Jet
Δm	Mass material removal [mg/s]
d	nozzle diameter [mm]
p	pump pressure [MPa]
P_h	hydraulic power [kW]
v	feed speed rate [mm/s]
z	stand-off distance of nozzle from material [mm]
f	frequency [kHz]

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1. Introduction

Destructive effect of water on various materials is recognized in long term view Cook [1]. Clean water jet (WJ) or abrasive water jet (AWJ) is currently used for cutting of wide range of materials. High pressure WJ and AWJ reaches technological and economical limits. Nowadays is known material destruction using lower pressure, fortified by additional device. Pulsating water jet (PWJ) can by applicated in various industry sectors. Numerous way of approach to create discontinual flow are recognized. Modulation of continual flow, which subsequently starts to form into pulses is considered as most perspective.
The first is represented by internal mechanical modulators of the flow rate, which Nebeker & Rodriques [2] and Nebeker [3-6] deal with. The authors proposed a mechanical device for achieving pulsating jet that is located in a nozzle and causes the forced periodical modulation of the jet. However, this method has not been applied in practice because the service life of moving components in a nozzle was very short.
The second method of modulation of continuous jets is represented by devices working on the principle of self-resonating nozzles. The authors who discussed these issues were Johnson et al. [7], Chaine et al. [8], Chaine & Conn [9] and Sami & Anderson [10]. Self-resonating nozzles modulate the water jet by creating impact pressure during the flow of liquid through the outlet of a resonant tube that runs back to the inlet where a stationary oscillation is created. If the frequency of impact pressure corresponds to the natural frequency of flow, pressure resonance occurs, and the water jet starts to create discrete annular whirls creating pulses or cavitation Foldyna [11]. Experiments under water were carried out using self-resonant nozzles Gau et al. [12], where paraffin was the cutting medium and cavitation disintegrated material under water.

The generation of ultrasonic vibrations using a natural device, an ultrasound converter, is the third method of continuous water jet modification. This method allows the change of frequency and deviation of amplitude of an actuator. Magnetostriction and piezoelectric actuators are used for the generation of vibrations Foldyna [11]. The first authors dealing with these issues were Danel & Guilloud [13]. Later, the principle of ultrasonic modulation of jet and options for pressure transmission of vibrations were studied by Puchala & Vijay [14], Vijay [15], Vijay & Foldyna [16], Foldyna & Švehla [17], Foldyna et al. [18-22] and Říha & Foldyna [23].
PWJ is also applied as a tool for the disintegration of rocks and stones Vijay et al. [24], redevelopment of concrete structures Sitek et al. [25], Foldyna [27], Dehkhoda [26], surface finish of decorative stones Bortolussi et al. [28], and in the engineering industry for the removal of scale from steel Hnizdil & Raudensky [29]. The impact of pulsating water jet on the erosion of metals is intensively examined by Foldyna et al. [30, 31], Klich [32, 33]. Pulsating water jet can also be applied in medicine, i.e. in dental hygiene Sharma et al. [34], in orthopaedy and traumatology Hloch et al. [35], Kural et al. [36], Di Pasquale et al. [37] and in the field of dermal medicine Akbari et al. [38] and Stutz & Krahl [39].
The use of micro PWJ also appears in the field of fine electronics, where the area of cooling microchips using PWJ Hew et al. [40] is examined.
Surface integrity after impact of acoustically excited water jet with round nozzle is not yet examined. Surface integrity involves functional properties of surface such as, surface topography, chemical changes, physical changes, structural changes, depth and grade of strengthening, residual stress.
Presented research was focused on surface integrity evaluation of brass CW614N after impact of PWJ from the perspective of structural changes in surface layer and strengthening in subsurface layers. Experiment was held in cooperation with the Faculty of Manufacturing Technologies in Prešov; Institute of Geonics of the CAS, v.v.i. in Ostrava - Poruba and with Institute of Materials Research, Slovak Academy of Science in Košice. Nano indentation measurements were realized in Institute of material research of SAV in Košice. Experimental part of research was realized in Institute of Geonics of the CAS, v.v.i. in Ostrava.
The principle of creating pulses excited in the aforementioned way is based on the generation of vibrations in an ultrasound converter, which are transmitted to water in a nozzle using a waveguide and ultrasonic tool. The water jet exiting the nozzle is continuous, yet it starts to form individual clusters of fluid in a certain distance from the nozzle. The material is subsequently disintegrated by the shock impacts of water clusters with high kinetic energy.

2. Experimental set up

2.1. Technological set up

Experimental set up showed on fig. 1 consist of 2D XY table PTV WJ2020-2Z-1xPJ, cutting head, round nozzle StoneAge with required diameter, hydraulic high pressure plunger Hammelmann HDP 253 (max. operating pressure 160 MPa and max. flow 67 l/min), ultrasound device Ecoson Wj-UG_630-40 (for pulse generating) and industrial robot ABB IRB 6640-180//2.55 for manipulation with cutting head.

2.2. Experimental material

Brass identified as **CW614N** (**Ms.CuZn39Pb3)** (tab. 1, 2) was the first experimental material. It is characterized by high resistance to corrosion, high tensile strength. Brass CW614N has limited cold ductility, and they are harder and stronger. It is used for machining, and it is also suitable for forging. Lead is added to the alloy for better workability. This type of material is usually used for the manufacture of high-speed components of machining, architectonic pressings, locks and hinges. [41]

Table 1. Chemical composition of brass CW614N.

Chemical composition - **BRASS CW614N** [%]							
Cu	Cd	Fe	Pb	Ni	Sn	Zn	Al
57,7	< 0,0075	0,1	3,3	< 0,3	0,2	rest	< 0,01

Table 2. Mechanical properties of brass CW614N [42].

Mechanical properties Brass **CW614N**			
Tensile strenght Rm [MPa]	Yield strenght $R_{p0.2}$[MPa]	Elongation L_5 = 100 mm A [%]	Hardness HB
430	250	6	120

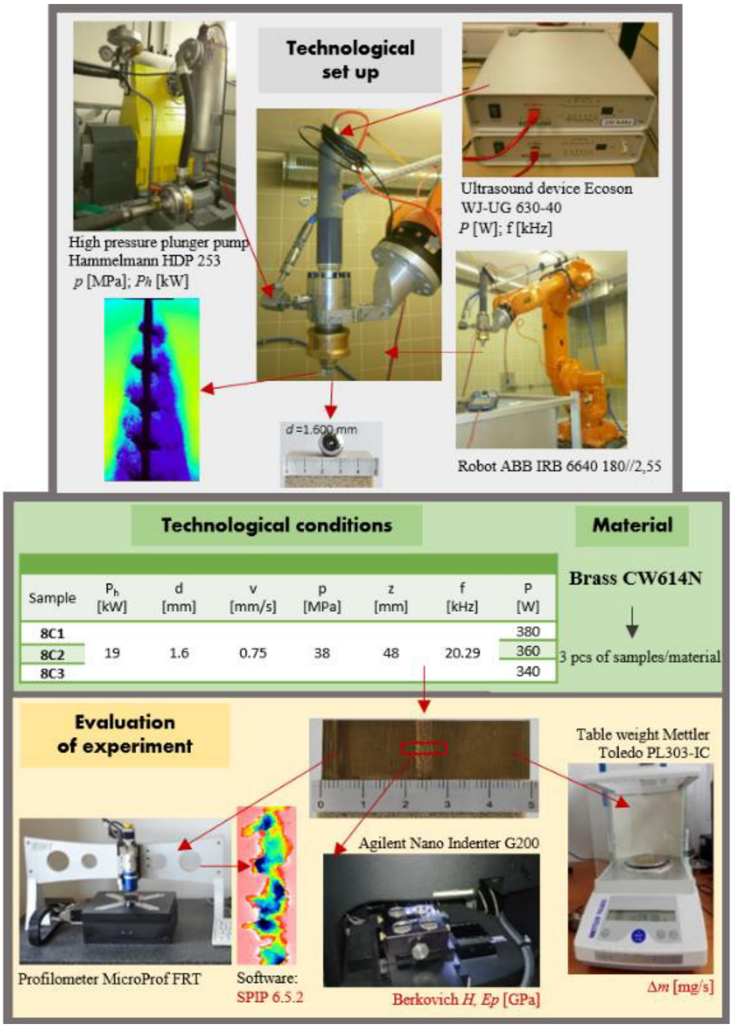

Figure 1. Experimental set up.

2.3. Experimental investigation

Experimental parts with dimensions 5x20x50 mm were prepared in count 3 pcs. Technological conditions were set according to table shown in fig.1. Variable factor of experiment was ultrasound power on values P = 320, 340 and 360 W. Each sample was

weighted using table weight Mettler Toledo PL303-IC (fig. 1.) before and after disintegration and subsequently mass material removal Δ*m* [mg/s] (tab. 3) was calculated.
Topography measurement was realized using optical profilometry with contactless optical profilometer MicroProf FRT (fig. 1) operating with white light. Subsequently topography and grooves surface were evaluated in software SPIP 6.5.2.
On account of strengthening evaluation were experimental samples cut perpendicular to grow. Device Struers Secotom 15 was used for cutting samples. Samples were embedded in dentacryl on BuehlerSimpliMet 3000 and subsequently grinded and polished using Struesrs Tegramin – 30 with application of mono crystal diamond suspension with grain size according to metalogram.
Strenghtening in subsurface layer was investigated by nanoindentation on device Agilent NanoIndenter G200 (fig. 1) using Berkovich indentor in direction transverse to surface created by PWJ. First phase of measurement is continual loading to max force F = 200 mN. Second phase is characterized by controlled releasing of force to zero value. Subsequently elastic regeneration was determined from depth of penetration to material.
Graphical dependences of measured values on loading force F are shown on indentation curves (fig.5). One indentation curve for each measurement was created, subsequently were identified values of indentation elasticity modulus [GPa] and hardness H [GPa].
Measurement was performed in three lines, ten indents in each line with step 100 μm (first indent 40 μm from edge of grow). Average values for each distance were calculated and subsequently graphical dependences of distance on elasticity module and hardness were created.

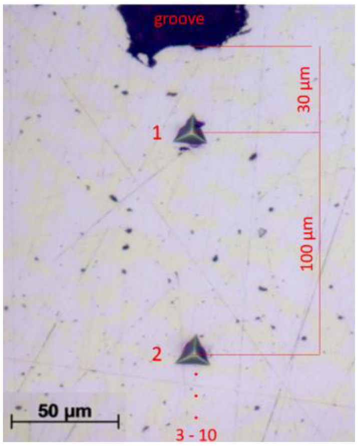

Figure 2. Distances between indents.

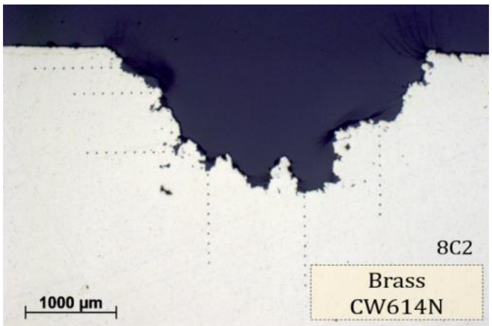

Figure 3. Disposition of indents on sample 8C2.

3. Results

Primary objective of experimental research was evaluation of surface integrity after disintegration of brass CW614N by acoustically excited pulsating water jet from perspective of surface topography, structural changes in surface layer and strengthening in subsurface layer.

3.1. Evaluation of surface topography and changes in surface layer

Optical profilometry was used to determine maximal depth of penetrance of PWJ into base material. Fig. 4 shows profiles of individual grooves. As shown on figures grooves have similar mass material removal Δm [mg/s], despite of variable values of ultra sound power P [W]. According to surface topography is shape of grooves inconsistent, but some shared properties can be find as:

- Absence of strict boundaries of grooves
- Most of grooves edges have rounded character
- Contoured surface with protrusions and depressions in random shapes and destinations
- The predominant sharp characteristics of protrusions and depressions
- Extrusion of material above upper level of the groove

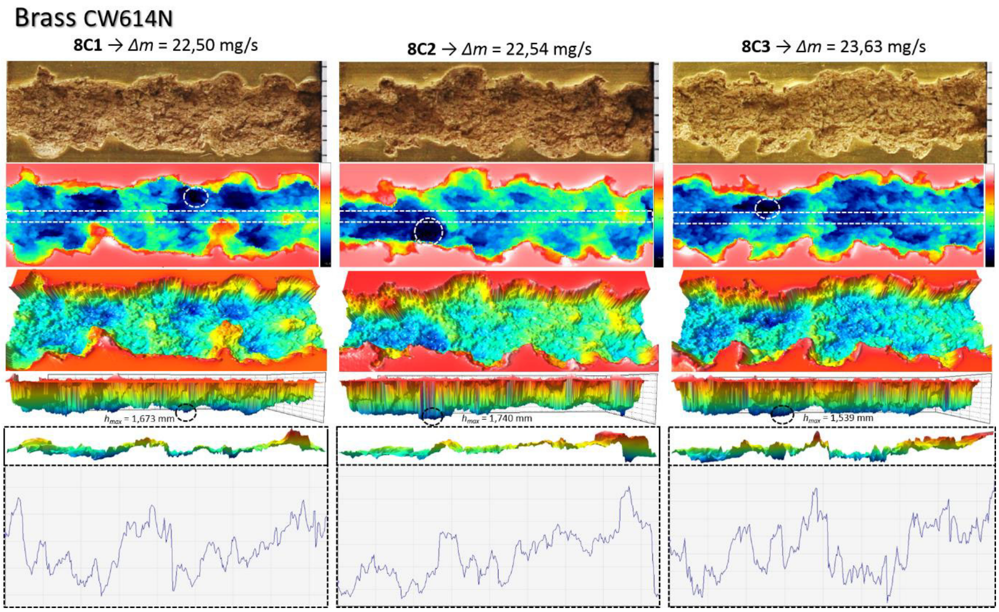

Figure 4. Comparison of profiles and topographies of grooves in CW614N.

Table 3. Comparison of values Δ*m* [mg/s] and h_{max} [mm].

Sample	P [W]	BRASS CW614N	
		Δm [mg/s]	h_{max} [mm]
8C1	380	25,50	1,673
8C2	360	22,54	1,740
8C3	340	23,63	1,593

Changes in surface layer after disintegration by PWJ were evaluated according to mass material removal Δm [mg/s] and maximal depth of penetration of PWJ into material h_{max} [mm], with variable ultrasound power no values P = 320, 340 and 360 W.
For brass CW614N maximal mass material removal Δm [mg/s] was detected with ultrasound set on highest level P = 380 W. Values of mass material removal Δm [mg/s] at P =360 and 340 W reached similar values with slightly higher when P = 340 W. Maximal depth of penetration h_{max} [mm], was observed with ultrasound power on middle level P = 360 W.

3.2. Evaluation of subsurface layer strengthening

It can be assumed that during transition of PWJ is material not only mechanically removed but also compressed at the point of last contact between PWJ and base material. To examine the elastic and plastic properties of materials after transition of PWJ was chosen experimental nanoindentation method. As representative sample was selected sample labeled 8C2.

Fig. 5. shows indentation curves representing response of tested material to indentation. As a representative curve was selected indentation curve no. 11 (first indent in second series of measurement) for both materials and in positions below and beside groove. Initial deformation was elastic. With increasing loading force up to F = 200 mN stress under indenter rise above yield strength of material and plastic deformation appears. Second phase is characterized by releasing force and thus penetration of indenter declines with material relaxation. Indentation curves (fig. 5) describe materials partial relaxation and shows elastic-plastic characteristics of base material. Table below (tab. 4) contains average values of H [GPa] and E_p [GPa] for material

CW614N and standard deviations of measured values. Measurements were preformed below and beside groove (fig. 3) and also reference measurement in area unaffected by PWJ. Subsurface strengthening was evaluated based on material hardness H [GPa] and indentation modulus of elasticity E_p [GPa]. Examined sample was labeled 8C2.

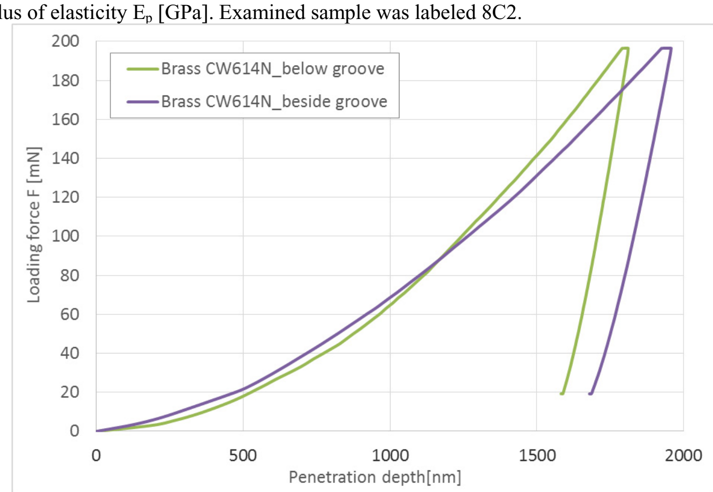

Figure 5. Indentation curves.

Table 4. Average values of hardness *H* [GPa] and indentation elasticity modulus E_p [GPa] – brass CW614N.

Brass CW614N												
Indent order			1	2	3	4	5	6	7	8	9	10
Distance from the surface L_i [μm]			30	130	230	330	430	530	630	730	830	930
Hardness H [GPa]												
8C2	Unaffected mat.	H [GPa]	1.665	1.697	1.705	1.530	1.785	1.717	1.719	1.696	1.731	1.701
	Below groove	H [GPa]	1.909	1.741	1.585	1.612	1.517	1.486	1.506	1.577	1.559	1.561
		σ [GPa]	± 0.337	± 0.122	± 0.057	± 0.068	± 0.080	± 0.035	± 0.086	± 0.059	± 0.132	± 0.144
	Beside groove	H [GPa]	1.815	1.731	1.646	1.621	1.579	1.606	1.526	1.540	1.552	1.508
		σ [GPa]	± 0.627	± 0.213	± 0.068	± 0.074	± 0.103	± 0.097	± 0.058	± 0.029	± 0.046	± 0.046
Indentation modulus od elasticity E_p [GPa]												
8C2	Unaffected mat.	E_p [GPa]	88.120	90.596	94.238	86.441	91.251	91.489	91.330	91.324	88.644	89.078
	Below groove	E_p [GPa]	97.410	101.075	103.212	106.166	105.377	102.477	104.308	102.324	101.910	102.307
		σ [GPa]	± 7.395	± 2.046	± 2.369	± 3.870	± 7.365	± 5.912	± 1.149	± 4.968	± 3.560	± 8.471
	Beside groove	E_p [GPa]	63.834	97.463	98.458	101.586	102.131	105.043	107.805	102.809	103.924	106.109
		σ [GPa]	± 12.628	± 0.382	± 5.379	± 1.789	± 5.156	± 2.584	± 3.287	± 2.764	± 1.891	± 4.138

Graphical dependence shown on following figure (fig. 6) describes change of material hardness. Significant changes in H [GPa] was observed in distances till $L_i \approx 230$ μm. Values of hardness in strengthen area decreasing from 1.91 to 1.58 GPa below groove and from 1.81 to 1.65 GPa beside groove. Interesting effect occurs in larger distances from groove where values of H [GPa] are slightly lower than average value H ≈ 1.69 GPa in unaffected area. Average values in distance $L_i \approx 230$ μm, are – below groove H ≈ 1.54 GPa and beside groove H ≈ 1.56 GPa.

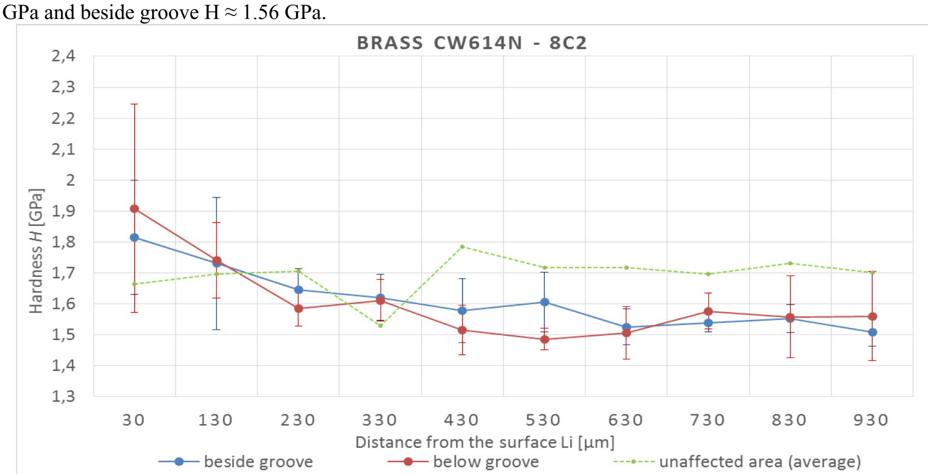

Figure 6. Comparison of chances in hardness *H* [GPa] below, beside groove and in not affected area in dependence of distance from groove – brass CW614N, sample 8C2.

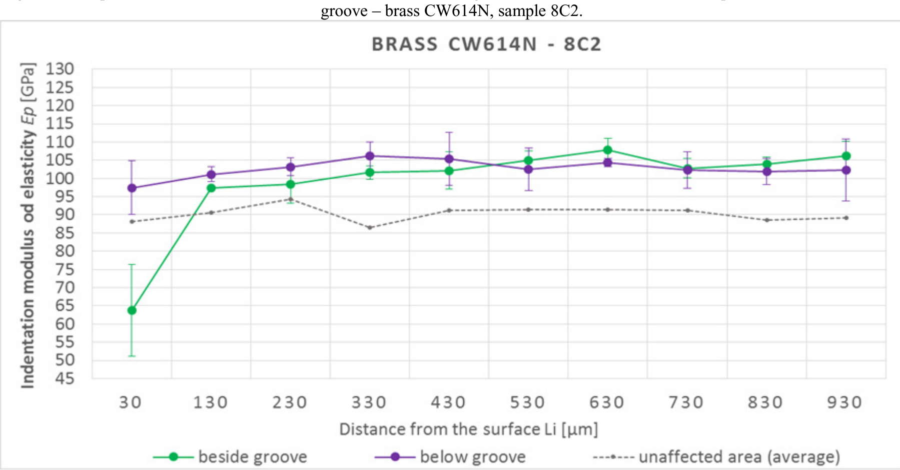

Figure 7 Comparison of chances in indentation modulus of elasticity E_p [GPa] below, beside groove and in not affected area in dependence of distance from groove – brass CW614N, sample 8C2.

Indentation modulus of elasticity E_p [GPa] values measured beside groove increase to distance $L_i \approx 330$µm. Paradoxically value of E_p for first indent in distance $L_i \approx 30$ µm is $E_p = 63.83$ GPa and in interval $L_i \approx 130 – 330$ µm values E_p increasing from 97.46 to 101.59 GPa. In greater distances is value E_p stabilized on value approximately 104.64 GPa. First indent obtained below groove in distance $L_i \approx 30$ µm do not show as extreme valuea as beside groove. Values obtained below groove slightly increase to distance $L_i \approx 330$ µm in interval $E_p = 97.41 – 106.17$ GPa. Above value $L_i \approx 330$ µm is modulus of elasticity stabilized $E_p = 103.11$ GPa.

4. Conclusions

I. According to surface topography is shape of grooves inconsistent, but some shared properties can be find as:
- Absence of strict boundaries of grooves
- Most of grooves edges have rounded character
- Contoured surface with protrusions and depressions in random shapes and destinations
- The predominant sharp characteristics of protrusions and depressions
- Extrusion of material above upper level of the groove

Surface quality considering size, shape, and distribution of the protrusions and depressions is low quality. Therefore accuracy disintegration PWJ using a circular nozzle at selected technological conditions is very low. Boundaries of the groove are random, which leads to conclusion that the technology is not suitable for precision machining.

II. Assessing influence of ultra sound power on mass material removal Δm [mg/s] and maximal depth of penetration h_{max} [mm], was not proven significant influence. On the other side can be assumed influence of chemical composition on Δm [mg/s] and h_{max} [mm].

Findings provide information about ultrasound impact on mass material removal Δm[mg/s, but is not possible to clearly determinate the influence, because into process income several other variables such as temperature of water, heat of machinery parts, vibration, clamping of the workpiece and so on, which can be eliminated but not negate. From the results can to be define significant impact of ultrasound power P [W] on maximal depth of penetration h_{max} [mm].
Influence of the chemical composition to process of disintegration is shown for experimental samples made of brass CW614N. Structure of the brass CW614N consist of two main components Cu (57.70 %) and Zn (38.38 %). The reason of obtain maximal depth $h_{max} = 1.174$ mm at value of ultrasound power P = 360 W can be caused by penetration of the PWJ into soft material component (Zn). It can be stated that mass material removal is depend on material structure and composition.

III. Indentation curves shown in figure 5 demonstrate characteristic of brass CW614N to partially regeneration and also represent elastic – plastic character.

IV. Creation of subsurface strengthening in examined material was proven based on nanohardness measurement H [GPa]. Measurements of nano hardness below and beside groove achieved similar values. Results of nanoindentation H [GPa] are $L_i \approx 230$ µm, below → H = 1.91 – 1.56 GPa, beside → H = 1.82 – 1.65 GPa.

V. Based on indentation elasticity modulus *Ep* [GPa] was proved lower elasticity of base material in strengthened area. In the fact of this can be stated, that lower pressure is necessary for deformation and thus disintegration is more effective.

The conclusions of the present research suggest the need for a deeper and wider examination of the possibility of disintegration of materials pulsating water jet. In this area, an intensive research to evaluate changes in the operation of various technological factors, impact of changes in shapes of nozzles, the use of other, not only in metallic materials. The research also takes place also in the possibility of using self-resonating nozzles, forming a pulsating flow without the need for ultrasound equipment for the generation of pulsation.

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