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EXPERIMENTAL INVESTIGATION OF THE SURFACE PROPERTIES OBTAINED BY CUTTING BRASS-353 (α+β) WITH AN ABRASIVE WATER JET AND OTHER CUTTING METHODS

PREISKAVA LASTNOSTI POVRŠINE MEDENINE 353 (α+β) PO REZANJU Z ABRAZIJSKIM VODNIM CURKOM IN DRUGIMI METODAMI REZANJA

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In the manufacturing industry different methods are used to provide the fastest, cheapest and the most cost-effective way of facilitating the process of cutting with the minimum surface deformation. Apart from the conventional methods, non-traditional methods such as abrasive water jet (AWJ), laser, plasma, underwater plasma and wire erosion are used intensely for the cutting of hard-to-cut materials and products. Research has been conducted on the AWJ method. Brass materials are widely used in industry. In this study the results of the cutting process for brass material with AWJ were investigated. Based on the results the ideal cutting method for the investigated material was found to be AWJ.

Keywords: cutting methods, unconventional cutting, surface properties

V industriji se uporabljajo različne metode za hitro, cenejše in stroškovno bolj ugodne metode rezanja z minimalno deformacijo površine. Poleg navadnih metod za rezanje trdih materialov in proizvodov se uporabljajo tudi netradicionalne, kot je abrazijsko rezanje z vodnim curkom (AWJ), laser, plazma, podvodna plazma in žična erozija. Izvršene so bile raziskave AWJ. Medenina se pogosto uporablja v industriji. V tej študiji je bil preiskan postopek rezanja medenine z AWJ. Glede na dobljene rezultate je ugotovljeno, da je za preiskovani material najboljša metoda abrazijsko rezanje z vodnim curkom.

Ključne besede: metode rezanja, neobičajno rezanje, lastnosti površine

1 INTRODUCTION

Cutting quality can be determined by measuring the surface roughness, dimensional tolerances, etc. In the cutting processes for different materials, there are no significant differences in general macro-morphological surface properties. For example, the surface obtained on cut glass is the same as on metal, ceramic and composites. However, when examined at the micro-level, micro-qualities of surfaces vary depending on the differences between the cutting mechanisms of different methods. The properties of the surfaces obtained with an abrasive water jet are listed below:

- The surface is not affected by thermal impacts or heat.
- No crusting is found on brittle materials. Surface is almost free of refractions.
- An insignificant hardness alteration may occur on the surface.
- The width of the cut may be narrowed depending on the diameter of the jet.
- Abrasive fragment sedimentation may occur in the material.
- Small chamfers may occur in the holes to the surface.

The quality of the obtained surface could be improved by increasing the power spent for each unit of the cutting length. A better surface quality is obtained by increasing the water pressure, decreasing the jet speed, increasing the abrasive magnitude rate in the jet and selecting a larger nozzle. Abrasive-surface properties as well as abrasive-particle shape and dimension are important factors. The width of the cutting channel is controlled with the mixture tube nozzle and the jet speed[1].

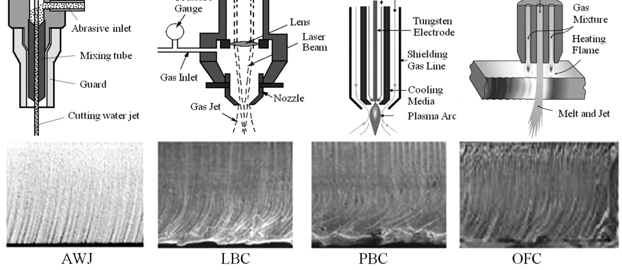

Figure 1: Surfaces obtained with the jet flow and the quality zones[2,3]
Slika 1: Površine, dobljene s curkom, in njihova kvaliteta [2,3]

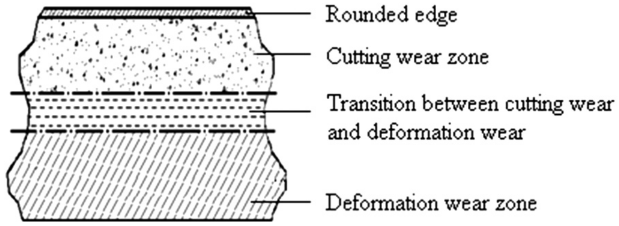

Figure 2: Surface sections cut by the abrasive water jet[4]
Slika 2: Področja površine reza pri abrazijskem vodnem curku[4]

Characteristics of the cut surface: When examined in order to determine the surface quality, the surfaces cut with different methods are similar. Surface roughness is defined with the waves on the surface and the size of the wave is proportional to the jet diameter (**Figure 1**)[2,3].

While the wave size depends on the jet diameter and the penetration of the abrasive water jet, the surface roughness is related to the micro-interaction between each abrasive and the workpiece. The cutting quality depends on the inner physical effects caused by the jet and the external factors such as various cutting parameters, nozzle vibration and job fragment. When a surface cut with abrasive water is examined, three different sections can be seen as shown in **Figure 2**[2,4].

1. In the upper corner of the cut surface there is a small curve caused by the hitting articles departing from the jet. This section is usually accepted as an ignorable edge impact.

2. This is a smoother surface section located under the first section. This section is formed by the particle erosion caused by the abrasive particles hitting the surface at a low impact angle. Experimental studies performed recently have proven the fact that a 1.3 µm surface-roughness quality can be obtained on this section.

3. The cutting capability is reduced as the kinetic energy of the abrasives decreases and the jet looses it regularity. This is a transition section where the second cutting mechanism prevails and the surface is formed by faults due to parallel jet deviations. In this second cutting mechanism, the impulse angle of the hitting particles against the surface is bigger and defined as "the deformation erosion". The deformation abrasive mechanism is realized by the particles hitting the surface at a bigger angle. When the travelling speed of the jet is reduced, the transition area between the second and third sections is smaller[4].

If a quality cutting process is required, the parameters must be adjusted and the cutting process must be completed before entering the deformation abrasion section. By adjusting the parameters, the flaking will also be avoided. By selecting a sufficiently low lateral speed level, a considerably smooth surface without any flaking will be obtained on the first section. Smaller abrasive particles and a bigger abrasive mass of the jet flow will reduce the surface-roughness value. A particle with bigger dimensions will consequently cause a larger cut area and the surface will be rougher (it will have a larger roughness value)[3–5].

Increasing the abrasive mass of the jet or reducing the jet speed will improve the quality by increasing the number of the particles hitting against the surface being cut. When greater cutting speeds are used in a rough cutting operation, each of the three sections can be seen on the surface. A deviation of the jet on the third section and a formation of parallel lines appear as a function of the parameters of lateral speed alterations, abrasive feeding-flow rate, liquid pressure and nozzle geometry. Abrasive substances form holes and pockets at the lower parts, where they are accumulated and embedded during the rough cutting operations. Such residual particles may damage the nozzle during the operations. These negative effects must be taken into consideration. When the surface quality and energy of the particle are considered, we find that as the cutting depth gets bigger the deviation of the jet increases causing an increase in the energy of the particle.[6,7] Thus, a greater energy applied on the surface show that the surface roughness and surface waviness are more robust and there are more deviations of the jet (**Figure 3**)[1,4].

Comparison of the abrasive water jet with the alternative methods: In **Figure 4**, the inverse relationship between the thickness and lateral feed rate is shown, considering the surface quality of the cutting surface. The AWJ method has the lowest lateral feed rate, while the plasma method has the highest feed rate. An overall comparison of the abrasive water jet and the alternative cutting methods in **Table 1** shows that the most efficient cutting method is the cutting with AWJ, being independent of the material thickness and its characteristics. However, there are some disadvantages of this method. The most important one is the dependency of the system and the cutting parameters on several variables. Because of this dependency, it is hard to provide a continuous

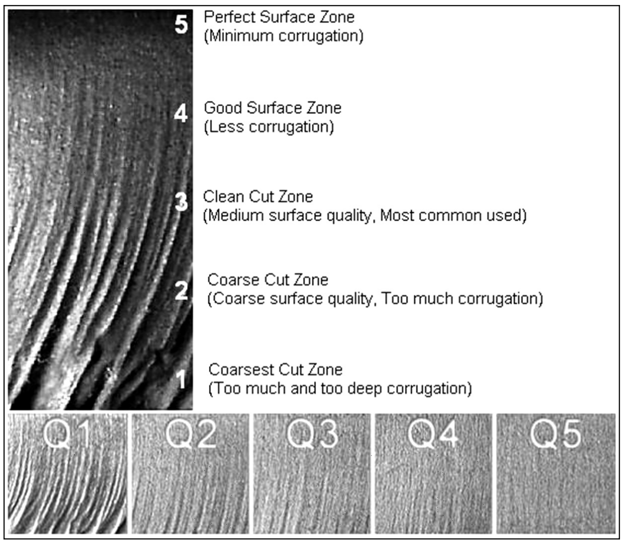

Figure 3: Cut-face quality zones based on jet flow[143]
Slika 3: Področja na površini, rezani s curkom[1,4]

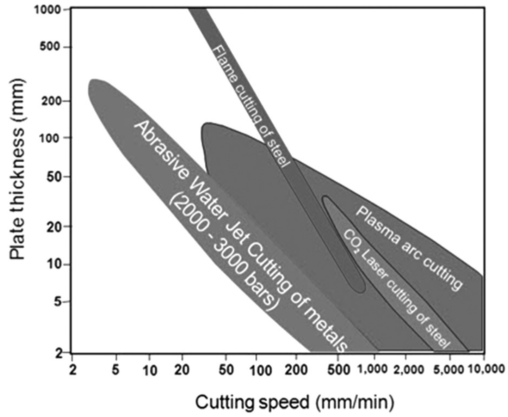

Figure 4: Comparison of the cutting abilities of different cutting methods using single-orifice jet beams[8]

Slika 4: Primerjava zmogljivosti različnih metod rezanja pri uporabi curka z eno šobo[8]

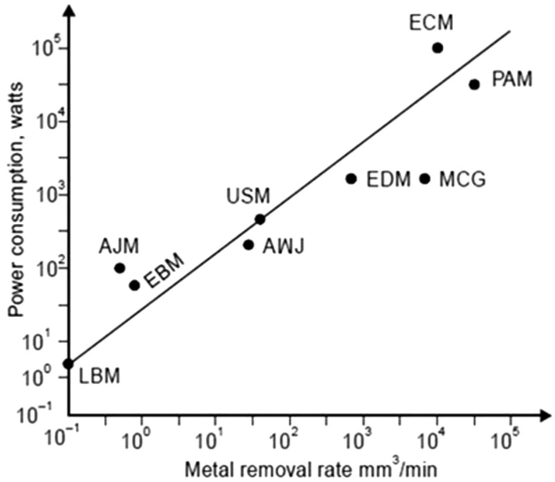

Figure 6: Comparison of the abrasive water jet with the other cutting methods[2,9,13]

Slika 6: Primerjava rezanja z abrazivnim vodnim curkom z drugimi metodami rezanja[2,9,13]

surface quality on the cutting surface. An increasing surface roughness is inevitable, as in the cases of laser, plasma, underwater plasma and oxygen-flame cutting methods[4,8–12].

There are several studies that compare the AWJ method with the other methods. The studies give different results due to different materials used. The techniques of AWJ and the other methods are compared by Hashish[2] as shown in **Figures 5a** and **5b**. This comparison is based on an evaluation of different processing methods in terms of their power levels and typical machining removal rates. There are various techniques for cutting materials (**Figure 6**)[2,9,13].

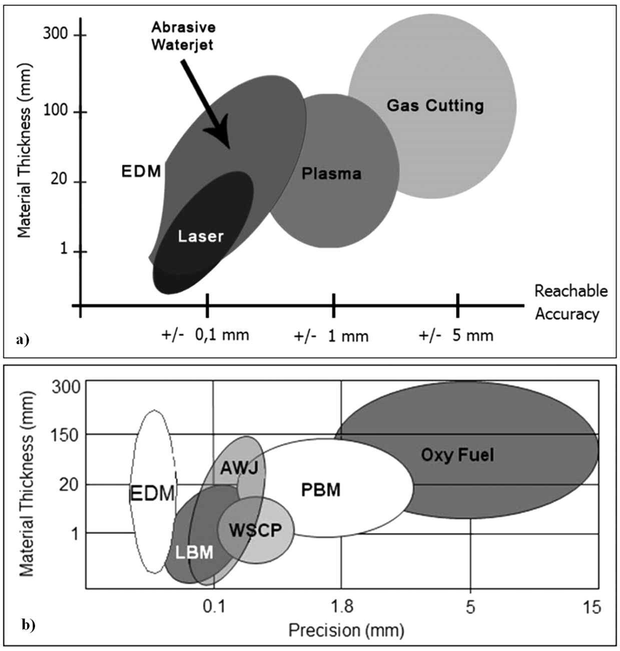

Figure 5: Comparison of the abrasive water jet with the other cutting methods[4,8]

Slika 5: Primerjava rezanja z abrazivnim vodnim curkom z drugimi metodami rezanja[4,8]

According to Hashish,[4] when compared with the traditional methods, AWJ forms a jet that is able to perform a cutting process with a very low energy and an intense energy distribution where most of the energy is lost due to friction. Just as in the other unipolar, ductile cutting operations, AWJ can be given directions perfectly well with a low energy applied, and it can perform cutting in all directions and can form considerably narrow cuts. Particularly due to no thermal effects on the cut materials, AWJ is more effective than the other competitive methods. However, in spite of the many advantages of the WJ and AWJ processing technologies, there are still certain disadvantages[2,14].

There are many studies comparing AWJ and the other methods. When these are examined different results are set forth depending on the material. Powell et al.[10] performed a study comparing the economical aspect of AWJ and laser. In their analysis they discussed the technical and commercial advantages and disadvantages of both methods and focused on the relative productivity of both processes. Ohlsson et al.[11] studied the pressure, abrasive flow and lateral-speed impacts on the steel cut with AWJ, the grey-cast-iron cutting depth and surface properties. Zheng et al.[14] made comparisons based on the quality and process costs, aiming at helping the users decide which methods would be more convenient for various applications. They made their comparison by using stainless steel with different thicknesses, soft steel and aluminum[12–14]. In the studies by Hashish and Ramulu,[13] focusing on the mechanical properties of laser and AWJ, they discussed the unique cutting abilities and characteristics of both methods. The researchers drew the attention of the users not only on the technical performance of the methods but also on how they affect the completed products; they evaluated the mechanical impacts of both methods on the titanium-alloy (Ti6Al4V) and steel (A286) materials[12]. As the optimum parameters have not been completely determined yet for the vast majority of these methods, there are plenty of other studies still being currently performed. The best data to set forth the superiority of AWJ is probably the figure given below. Furthermore, a graph is given indicating the capability of the method with respect to material thickness and a general comparison is given in **Tables 1** and **2**[1,9,15–17].

Applications of various machining methods are summarised in **Tables 2** and **3**. The machining characteristics of different non-conventional processes can be analyzed with respect to metal-removal rate, tolerance maintained, surface obtained, depth of surface damage and power required for machining. The physical parameters of the non-conventional machining processes have direct impacts on the metal removal as well as on the energy consumed for different processes. These

Table 1: Overall comparison of abrasive water jet and the alternative cutting methods [1,9,16]
Tabela 1: Primerjava abrazijskega vodnega curka z drugimi metodami rezanja[1,9,16]

Comparison of Disconnections by Water Jet and the Other Machining Methods								
Comparison Factor	Abrasive Water Jet	Laser Cutting	Plasma Cutting	Underwater Plasma	Wire EDM	Milling Cutting	Band Saw	Oxygen Cutting
Material Thickness	A	C	B	B	A	B	B	A
Cutting Quality	A	A	C	B	A	B	B	C
Lateral Speed	B	A	B	B	B	B	A	B
Multi-Purpose Use	A	D	B	B	B	B	B	C
Heat Affected Zone (HAZ)	A	D	D	C	C	B	B	D
Sensitive Cutting	A	A	B	B	A	A	C	D
Secondary Process Requirement	A	B	B	B	B	B	C	C
Chip Formation	B	C	C	C	A	B	D	B
Production Flexibility	A	B	C	C	B	A	C	D
Overall Process Time	B	B	D	D	B	B	A	C
A: Excellent B: Good C: Acceptable D: Unacceptable								

Table 2: Material applications of some machining methods[1,9]
Tabela 2: Uporabnost obdelovalnih metod glede na material[1,9]

Materials Applications								
Process	Aluminium	Steel	Super Alloys	Titanium	Refectories	Plastics	Ceramics	Glass
Ultrasonic Machining	C	B	C	B	A	B	A	A
Abrasive Jet Machining	B	B	A	B	A	B	A	A
Electrochemical Machining	B	A	A	B	B	D	D	D
Chemical Machining	A	A	B	B	C	C	C	B
Electric Discharge Machining	B	A	A	A	A	D	D	D
Electron Beam Machining	B	B	B	B	A	B	A	B
Laser Beam Machining	B	B	B	B	C	B	A	B
Plasma Arc Machining	A	A	A	B	C	C	D	D
Abrasive Water Jet Machining	A	A	A	A	A	B	A	A
A: Good Application B: Fair C: Poor D: Not Applicable								

Table 3: Process capabilities of non-conventional cutting processes[9,12]
Tabela 3: Zmogljivosti nekonvencionalnih postopkov rezanja[9,12]

Process Capability						
Process	Metal Removal Rate (mm/min)	Tolerance (μm)	Surface (μm) CAL	Depth of Surface Damage (μm)	Corner	Power (W)
Ultrasonic Machining	300	75	0.2–0.5	25	0.025	2 400
Abrasive Jet Machining	0.8	50	0.5–1.25	2.5	0.100	250
Electrochemical Machining	0.15	15	0.1–2.5	50	0.025	100000
Chemical Machining	150	50	0.4–2.5	50	0.125	–
Electric Discharge Machining	800	15	0.2–1.25	125	0.025	2 700
Electron Beam Machining	16	25	0.4–2.5	250	250	150 (average), 200 (peak)
Laser Beam Machining	0.1	25	0.4–1.25	125	250	2 (average)
Plasma Arc Machining	75000	125	Rough	500	–	50000
Abrasive Water Jet Machining	1.3	25	0.4–2.5	125	0.025	220
Conventional Milling of Steel	50000	50	0.4–5.0	25	0.050	3000

Table 4: Effects of different machining methods on equipment and tooling[9]
Tabela 4: Vpliv različnih metod obdelovanja na opremo in orodje[9]

Effects on Equipment and Tooling				
Process	Tool Wear Ratio	Machining Medium Contamination	Safety	Toxicity
Ultrasonic Machining	10	B	A	A
Abrasive Jet Machining	–	B	B	A
Electrochemical Machining	0	C	B	A
Chemical Machining	0	C	B	A
Electric Discharge Machining	6.6	B	B	B
Electron Beam Machining	–	B	B	A
Laser Beam Machining	–	A	B	A
Plasma Arc Machining	–	A	A	A
Abrasive Water Jet Machining	–	B	B	A
Tool Wear Ratio = Volume of work material removed / Volume of tool electrode removed A: No Problem B: Normal Problem C: Critical Problem				

Table 5: Economic performance of different machining methods[9]
Tabela 5: Ekonomičnost posameznih metod rezanja[9]

Process Economy					
Process	Capital Investment	Tooling and Fixtures	Power Requirement	Efficiency	Tool Consumption
Ultrasonic Machining	B	B	B	D	C
Abrasive Jet Machining	A	B	B	D	B
Electrochemical Machining	E	C	C	B	A
Chemical Machining	C	B	D*	C	A
Electric Discharge Machining	C	D	B	D	D
Electron Beam Machining	D	B	B	E	A
Laser Beam Machining	C	B	A	E	A
Plasma Arc Machining	A	B	A	A	A
Abrasive Water Jet Machining	B	B	B	C	C
Conventional Milling of Steel	B	B	B	A	B
A: Very Low Cost B: Low C: Medium D: High E: Very High *Indicates cost of chemicals.					

characteristics of different methods are given in **Tables 4** and **5**[9,17–19].

2 EXPERIMENTAL STUDIES

In this study the samples of (**Figure 7**) brass-353 (α+β) material 20 mm were cut with conventional (oxygen flame, hydraulic saw and freeze) and eight unconventional methods (abrasive water jet, laser-plasma arc, underwater plasma, wire erosion). The cutting edges obtained with these methods were examined in terms of their hardness and their effect on the microstructures. A comparison was made between the initial microstructures and the microstructures of the materials after cutting them with different methods; the effectiveness of the methods was evaluated. Water-jet-cutting parameters are shown in **Table 6**. Other cutting-process parameters were selected according to the parameters recommended by the lathe-manufacturing companies.

Chemical composition of the material: w/% (S 0.831, Pb 2.21, Zn 36.37, P 0.216, Mn 0.0778, Fe 0.293, Si 0.0829, Al 0.442, Cu < 59.23, Ni 0.237)

The average hardness level was calculated by taking the arithmetic average of the measured values at five different points at a given height on the surface. The value of HV 30 was calculated with an INSTRON WOLPERT TESTER hardness-measurement device. Additionally, hardness was measured in intervals 1 mm from the edge

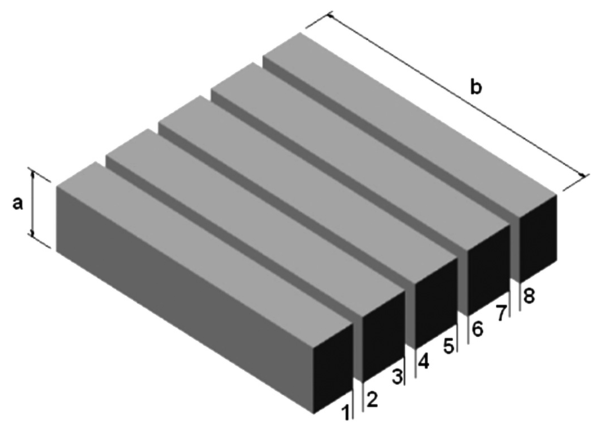

Figure 7: Samples after cutting
Slika 7: Vzorci po rezanju

Table 6: Cutting systems and cutting parameters
Tabela 6: Sistemi rezanja in parametri rezanja

Abrasive Water Jet Cutting			
Water consumption	≈ 3.5 L/min	Pump piston diameter	20 mm
System temperature of water	48 °C	Inlet pressure of water into the pressure booster	6 bar
Working pressure of the booster	200 bar	Inlet diameter of water into the nozzle	0.25 mm
Outlet pressure of water from the pressure booster	20 bar	Abrasive nozzle inlet diameter into the nozzle	0.75 mm
Water flow rate	3 L/min	Stand-off distance	4 mm
Outlet velocity of water from the nozzle	800 m/s	Water pressure at the instance of discharge	400 MPa
Temperature at the instance of cutting	≈ 55 °C	Jet angle at the nozzle	90°
Current consumption during work	380 V	Energy consumption	58 kW h
Amount of abrasive consumed	250 g/min	Material used in the nozzle orifice	Sapphire
Abrasive used	GMA Garnet	Chemical composition	$Fe_2O_3Al_2$ $(SIO_4)_3$
Abrasive hardness (Mohs)	7.5–8	Abrasive particle size	300 μm
Abrasive water outlet diameter from the nozzle	0.75 mm	Nozzle length	76.2 mm
Slurry content	18 %	Mixing tube length	88.9 mm
Mixing tube diameter	1.27 mm	Nozzle orifice life	40–50 h

Laser Beam Cutting			**Plasma Beam and Water Shield Plasma Cutting**	
Cutting rate (Lateral feed rate)		20 m/min	Cutting rate (Lateral feed rate)	20 m/min
Position rate		140 m/min	Plate positioning	By Laser
Laser power		1550 W	Current for maximum cutting	760 A
Main power supply		GW 0–100 %	Nozzle pressure	12 bar
Pulse type		Mega pulse	Operating pressure	24 bar
Pulse change frequency		2000 Hz	Operating frequency	50 Hz
Pulse time	NP(T)	1500 μs	Cooling capacity	16747 kJ/h
	SP(t)	120 μs		
Mod type		Sürekli mod (CW)	Nominal voltage	400 V
Focus distance		7.5 mm	Average sound level (A)	68 dB
Cutting gas		Nitrogen	Cutting gas	Oxygen + Nitrogen
Cutting gas pressure		1.2 bar	Maximum cutting thickness	35 mm
Cooling temperature		*TA* = 25 °C	Cutting capacity	4000 mm × 7000 mm

Oxygen Flame Cutting		**Wire Electrical Discharge Cutting**								
Cutting rate (Lateral feed rate)	20 m/min	Processing condition						C521		
Current for maximum cutting	760 A	Feed rate						3 m/min		
Nozzle pressure	10 bar	Processing conditions and parameters								
Operating pressure	20 bar	ON	OFF	IP	HP	MA	SV	V	SF	C
Operating frequency	50 Hz	006	15	17	2	15	0.3	0.3	005	0
Cooling capacity	16747 kJ/h	Voltage	32 V							
Receiver tank capacity	30 l	Current	5.6 A							
Nominal voltage	400 V	Wire tension	Level 8							
Average sound level (A)	68 dB	Wire feed rate	7 m/min							
Cutting gas	Oxygen+Propane	Control system	Fine APT							
Parameters for each cutting methods are selected in accordance with the machine manufacturers' recommendations.										

of the material towards the inner part along a linear line, so that the hardness changes depending on the heat distribution were observed. The microstructures of the main material and the cut edges were viewed with a PANASONIC WV-CP410 Model, Type N334, light microscope, with a magnification of 280-times. Alumina and diamond paste were used to examine the microstructure of the material in the polishing operation followed by the etching process when dipped in the mixture of 2 mL of HNO_3 and 98 mL of methane alcohol for 20 s.

Examination of different cutting methods in terms of the structural variations created on the materials: In order to perform metallographic examinations and find structural deterioration on the cut section of the material, a microstructure photo of the section resistant to the cutting process was taken as shown in **Figure 8**. For an accurate assessment, plenty of photos were taken from every cutting edge, and the deformations due to the cutting method formed on the material structure as well

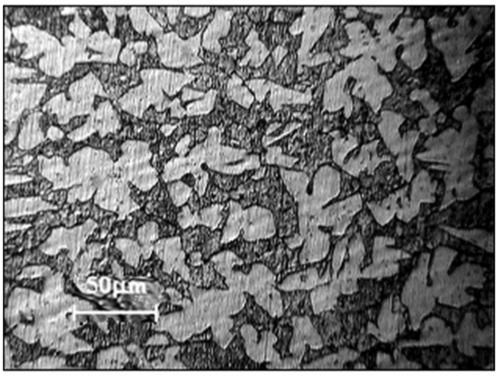

Figure 8: Microstructure of brass-353 (α+β)
Slika 8: Mikrostruktura medenine 353 (α+β)

as their changes were evaluated at the end of examining these photos.

Stripe (hydraulic) saw cutting: A considerably rough surface profile was obtained on the cut section. This cut profile was similar to the gear shape and it had a rather rough surface. Again, in the distance of approximately 25 µm a hard rough surface was observed due to the effect of cool deformation. No remarkable morphological change is seen, but there is a structural change caused by the deformation (**Figure 9a**).

Cutting with a milling cutter: A very flat profile was gained on the cut section. In the distance of nearly 10 µm, there is a remarkable, strong surface affected by the impact of cool deformation. Also, no strong structural change due to heat is noticed, but there is a change due to deformation (**Figure 9b**).

Cutting with underwater plasma: In the distances of approximately 75 µm the grain size of α and β phases got smaller and thinner but on the remaining section the grain size remained same. Also, structural deformations exist on the cut section due to excessive warming and fast cooling in the water (**Figure 9c**).

Laser cutting: On the cut section a rough cut profile is visible and due to a high temperature and cooling in air, the geometries of α and β phases turned into acicular forms. At the same time, the structure of the cut section was entirely deformed and α grains became different from their original forms. On the cut section and around it, a new rigid and fragile form emerged (**Figure 9d**).

Cutting with plasma: Owing to the heat effect, in the distances of approximately 75 µm, the grain size of α and β phases got smaller and over the main metal section the size of these grains got infinitesimally small as well. Moreover, due to excessive heat and fast cooling, the grains forming the structure got thinner. This trend continues towards the inner sections. A new hard and fragile structure was formed (**Figure 9e**).

Cutting with abrasive water jet: A very flat cut surface was obtained and in the distance of approximately 10 µm, a layer affected by cool deformation was observed. Apart from that, no structural alteration was observed on the cut section (**Figure 9f**).

Cutting with wire erosion: In the distance of approximately 20 µm the particle size of α and β phases got smaller and over the remaining part the particle size remained the same. Also, on the cut section, the particles forming the structure got thinner, more rigid and fragile due to excessive heat and rapid cooling (**Figure 9g**).

Cutting with oxygen flame: Over the cut section, the structure was entirely deformed and there was a new form, different from the original one. Due to an excessive heat input and rapid cooling in air, the geometries of α and β phases changed and α particles, apparently acicular, were also formed around the cutting section (**Figure 9h**).

In **Figure 10**, the surface-roughness values obtained by cutting thick brass-353 20 mm with different methods are compared. If this graph is carefully analyzed, it is clear that the roughest surface is obtained by cutting the material with the oxygen-flame method and the smooth-

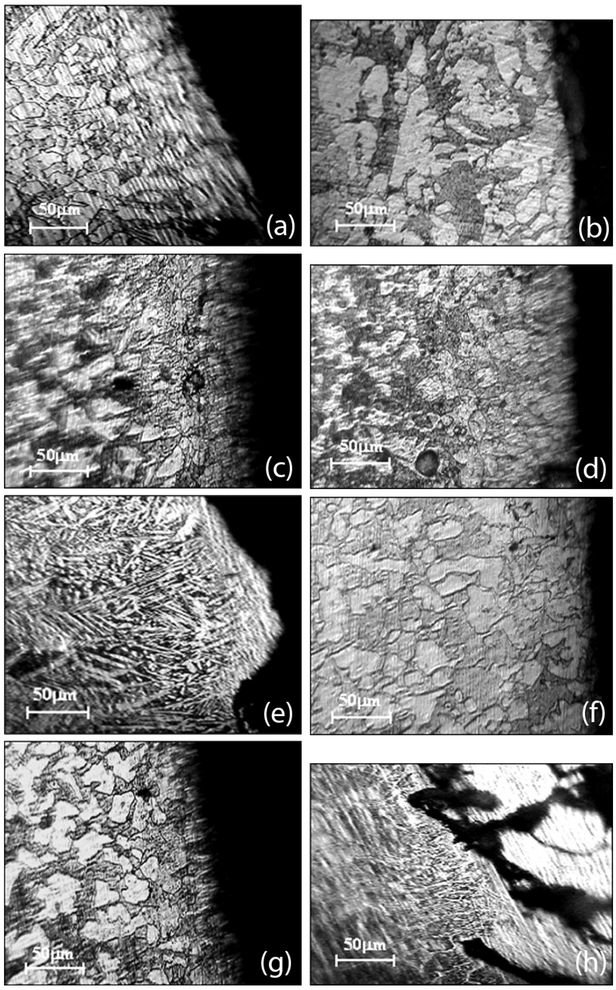

Figure 9: a) Stripe-saw cutting, b) milling cutting, c) underwater plasma cutting, d) laser cutting, e) plasma cutting, f) abrasive water jet cutting, g) wire-erosion cutting, h) oxygen-flame cutting
Slika 9: a) Rezanje s tračno žago, b) rezanje z rezkanjem, c) podvodno rezanje s plazmo, d) rezanje z laserjem, e) rezanje s plazmo, f) abrazijsko rezanje z vodnim curkom, g) rezanje z žično erozijo, h) plamensko rezanje s kisikom

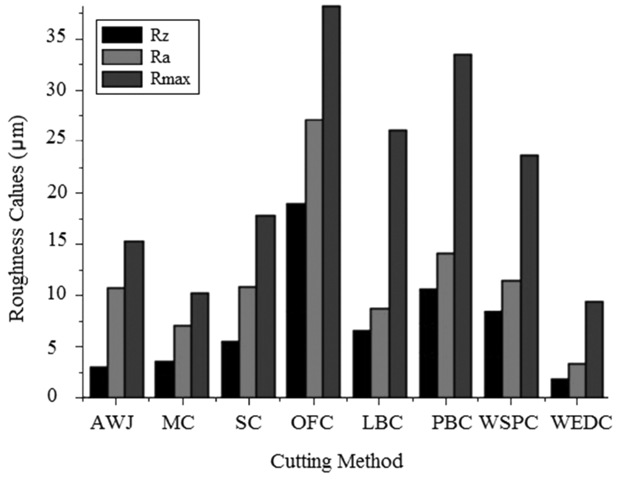

Figure 10: Comparison of the roughness values of cut faces obtained by cutting brass-353 with different methods

Slika 10: Primerjava hrapavosti površine reza pri rezanju medenine 353 z različnimi metodami

est surface is obtained by cutting it with the wire-erosion method.

The obtained outcomes of the study were evaluated using the unprocessed surface-microstructure photographs of the material shown in **Figure 11** and the surface microstructures of different methods shown in **Figure 12**. With the conventional cutting methods (in this study they include the milling cutter and the band saw) nearly the entire energy used for the machining was liberated as heat and a very small percentage of the energy turned into lost energy in the form of an elastic loss[14,15,19].

If the heat liberated in this way is not controlled, it will lead to a change in the metallurgical properties of the material. When the temperature is higher than the recrystallization heat of the material, it will lead to significant changes in the metallurgical properties of the material. The cooling conditions applied during machining will also affect the metallurgical forms of the material. Transformation of the energy into heat and the cooling conditions can be interpreted as the underlying reasons of the main metallurgical and mechanical changes such as the hardness of the material. The fundamental principle of the oxygen-flame cutting operation relies on rising the temperature of the material to the melting point. Rising the heat to the melting temperature and the successive cooling conditions will lead to significant changes in the mechanical and metallurgical formation of the material. This study also gave the expected result, according to which both metallurgical and hardness properties revealed the most significant changes to the material cut with this method.

The causes for the metallurgical changes and hardness variations in the materials are based on the frameworks of the methods applied. The laser, plasma and wire-erosion methods are based on the principle of cutting the material at the melting heat level. Different energy inputs and cooling conditions are the main causes for different metallurgical and hardness formations. Among the traditional methods, the hardness values obtained with the underwater-plasma (focusing) and wire-erosion methods were a little better than those obtained with the laser and plasma methods, because they were implemented in a preserving liquid and, thus, the temperature level was controlled. If a comparison is to be made between the executed cutting methods in terms of metallurgical properties and hardness factors on the basis of the original material structure and the hardness alteration, the best outcome is obtained for the AWJ cutting method. The hardness values for the surfaces cut with AWJ are fairly close to the original hardness ratios (for all the materials). This can be explained in terms of abrasion mechanisms. When cutting with AWJ, the heat variation remains very low (around Δt = 75 °C)[1,4,7]. This shows that no section (HAZ) is affected by the heat factor when using the AWJ cutting method. Taking this feature into account, it is clear that the AWJ cutting method is outstanding, not causing any form of metallurgical and mechanical alteration of the original material.

For the bras-353 materials used in this study, the hardness differences caused by different methods on the cut surfaces are shown in **Figure 11** and the impact rates of these effects are shown in **Table 7**. Following the AWJ cutting method, the second lowest change in the

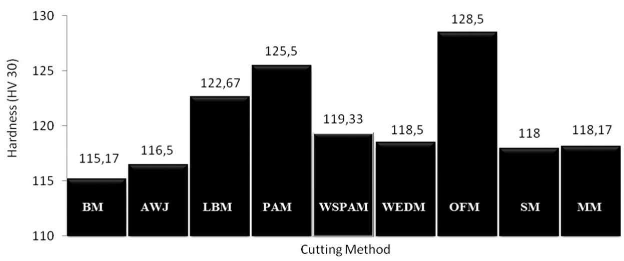

Figure 11: Comparison of the hardness values for the brass-353 (α+β) samples cut with different methods in comparison with the original hardness of the material core

Slika 11: Primerjava trdot medenine 353 (α+β), odrezane z različnimi metodami, v primerjavi s trdoto jedra materiala

Table 7: Hardness variations for brass-353 (α+β) cut with different methods

Tabela 7: Spreminjanje trdote medenine 353 (α+β)

Cutting Method	Brass-353	
	Hardness (HV_{30})	Change (%)
Base material	115.17	-
Cutting by Abrasive Water Jet	116.50	1.15
Cutting by Milling Cutter	118.17	2.60
Stripe (Hydraulic) Saw Disconnection	118.00	2.46
Cutting by Oxygen Flame	128.50	11.57
Cutting by Laser	122.67	6.51
Cutting by Plasma	125.50	8.97
Cutting by Underwater Plasma	119.33	3.61
Wire EDM Cutting	118.50	2.89

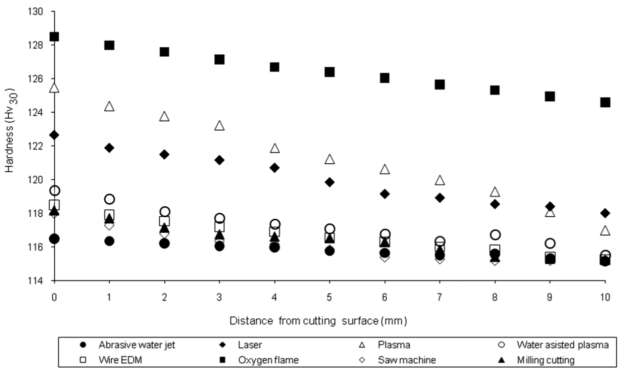

Figure 12: Hardness variations for brass-353($\alpha+\beta$) from the cutting edge to the center due to various cutting methods
Slika 12: Spreminjanje trdote medenine 353 ($\alpha+\beta$) od roba rezanja proti sredini pri različnih metodah rezanja

hardness is observed for the conventional methods such as the milling cutter and the band saw. This finding may be attributed to the fact that for the classical methods the cutting parameters are selected so as to avoid excessive recrystallization heat levels.

The depth of the section exposed to the heat also changes depending on the properties of the cutting method. Due to the changes in the metallurgical structures caused by the method, the measurement of the hardness, in the distance 1 mm starting from the cut surface towards the inner part, provides the information on the width of the section affected by the heat factor. The results of these measurements for brass-353 are shown in **Figure 12**. The most outstanding result observed from the graphs is the fact that there is a linear slope for the AWJ cutting method and, thus, no section on the brass material is affected by heat. The AWJ cutting method appears to be a process causing almost no change in the material hardness and metallurgical properties. On the other hand, the oxygen-flame cutting causes the highest level of change to the metallurgical and hardness properties. With this method, the hardness varies significantly from the surface to the core, and the whole material is affected by the heat factor. With the laser and plasma-cutting methods known as the biggest rivals to the AWJ cutting method, the hardness changes from the surface to the core, indicating that a large percentage of the surface of the material is affected by the heat factor. With respect to the metallurgical properties of the material, these methods cannot compete with AWJ.

When all the methods are taken into consideration, the hardness of brass changes constantly. This tendency, which is higher up to some point in steel materials, is reduced after a certain point[18,19]. This circumstance may be explained as a dependency on the heat conductivity of the material. For brass-353, the heat conductivity is higher than that of steel and, thus, the section affected by the heat factor is larger.

3 CONCLUSION

When the effects of different cutting methods on the metallurgical properties of the surface are taken into consideration, the AWJ cutting prevails outstandingly over the other cutting methods.

While different cooling and heat impacts caused by different cutting methods have important effects on the metallurgical properties of the material, in the AWJ cutting method, no section is affected by the heat as the temperature on the surface (HAZ) is not very high and there is no destruction of the original properties of the material. This finding shows that the mechanical properties of the material will remain unchanged as well.

Depending on the changes in the microstructure properties of the material, the section affected by the heat factor and the width of this section are subjected to structural change because of the high heat and cooling of some methods. Depending on the features of the cutting methods, some methods cause a rough particle formation and others cause a thin particle formation, due to instant cooling. Again, due to the effects of the methods, gas holes in the structure and microcracks are likely to emerge. In the AWJ cutting method, a high heat and instant cooling are the fundamental reasons for the microstructures not being destroyed.

When evaluating the eight different methods examined in this study on the basis of the changes in the microstructure properties of the section affected by the heat factor, it is clear that the least effective method is the oxygen-flame cutting and the most effective one is the AWJ cutting. Among the applied methods, the oxygen-flame cutting is viewed as the poorest method because of the variation in the hardness of the material it creates.

Depending on the effects of different methods on the metallurgical forms of the material, the mechanical properties of the material also change. In the experimental studies, the hardness values of the material, after using different methods, are different from the original values. This finding proves that the other cutting methods change the mechanical properties of the materials.

All the cutting methods tested in this study change the hardness of the material. This variation is changeable depending on the heat, temperature and cooling conditions occurring during the cutting operation.

When comparing different cutting methods with respect to the metallurgical properties and the hardness of the material, the best method is the AWJ cutting. This finding proves that during the AWJ cutting no section is affected by the heat factor (HAZ).

When the hardness changes caused by the heat factor are examined from the surface to the centre of the material cut with different methods, the AWJ cutting stands out as the most effective cutting method because with AWJ no section is affected by the heat factor and the cutting operation does not cause any metallurgical and mechanical changes to the material.

In the laser and plasma methods, considered as the most important alternatives to the AWJ cutting, the changes in the hardness from the surface to the center of the material show that, with these methods, the section affected by the heat is much larger than in the case of AWJ.

When compared with the other methods, AWJ is an effective and contemporary alternative cutting method in terms of the surface properties of the materials processed.

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