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Measurement of Fine Grain Copper Surface Texture Created by Abrasive Water Jet Cutting

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The paper presents results of experiments performed on copper with commercial purity to determine the influence of material grain size on both mechanical properties and texture of surface machined by abrasive water jet. An Equal Channel Angular Extrusion technology was used for creation of fine-grain copper samples. Hardness and grain size of fine-grain copper were measured, and, subsequently, surface of prepared copper samples was machined by abrasive water jet technology. Surface irregularities produced by the abrasive water jet were evaluated by means of surface profile roughness parameter *Ra*. It was found that the grain size of the material represents important factor affecting the final shape of surface topography in case of abrasive water jet machining.

Mjerenje teksture površine sitnozrnatog bakra dobivene abrazijskim rezanjem vodenim mlazom

Izvornoznanstveni članak

Ovaj rad prikazuje rezultate eksperimenata koji su napravljeni na bakru komercijalne čistoće, s ciljem određivanja utjecaja veličine zrna na mehanička svojstva i teksturu površine dobivene obradom abrazijskim vodenim mlazom. Za izradu uzoraka od sitnozrnatog bakra korištena je tehnika kanalno kutne ekstruzije. Mjereni su tvrdoća i veličina zrna sitnozrnatog bakra i posebno, površina priređenih bakrenih uzoraka koje je obrađena tehnologijom abrazijskog vodenog mlaza. Površinske nepravilnosti dobivene pri abrazijskom rezanju vodenim mlazom su ocijenjene pomoću profila površinske hrapavosti parametra *Ra*. Nađeno je da veličina zrna materijala predstavlja važan faktor koji utječe na konačan oblik topografije površine u slučaju obrade vodenim mlazom.

Symbols/Oznake

ECAE	- The method of Equal Channel Angular Extrusion - metoda jednake kanalno kutne ekstruzije	B_c	- deformation path, mm - put deformacije
AWJ	- technology by abrasive water jet - tehnologija rezanja vodenim mlazom	m_a	- abrasive type mass flow, g/min - maseni protok abraziva
σ_y	- tension at the yield point, MPa - naprezanje na granici razvlačenja	v_p	- traverse speed of cutting head, mm/min - poprečna brzina rezne glave
σ_0	- the constant of tension, MPa - konstanta naprezanja	l_r	- fundamental lengths, mm - osnovna duljina
k	- the constant - konstanta	h	- depth of cut, mm - dubina reza
d	- grain size of the material, mm - veličina zrna materijala		

1. Introduction

Continuous increase in use of properties of construction materials characterizes current trend in material engineering. One of the options to achieve better use of properties of material is represented by refinement of the material grain size without change of its chemical composition. Searching for possibilities of effective texture refinement of technical materials led to significant modifications of thermo-mechanical technology of material processing enabling achievement of grain sizes at the nanometre level. However, the use of these materials in the industrial sphere such as in the automotive industry (use of aluminium and magnesium alloys to reduce weight), for medical purposes (materials for surgical implants) or also in production engineering (machining of nanomaterials) still remains to be a substantial problem and further research is necessary in this field. In this context, also the metrology of final products from fine-grained materials is very important. Knowledge of roughness surface distribution provides first information about process of material creation, where surface defects are situated, etc. Therefore, it is imperative to perform the metrology of surface quality for every product.

2. Current state of the problem

Number of methods for generation of extreme plastic deformation to produce fine-grained materials was developed over the past 30 years; Figure 1 presents an overview of the most commonly used methods [1-2]. The methods are divided into three groups according to the method of creating extreme plastic deformation: i.e. by pressing, extruding, and rolling. The method of Equal Channel Angular Extrusion (ECAE) that was used in the experimental part of our research to produce copper samples with different grain sizes is described in more detail in the following part. The ECAE method is based on the extreme deformation of massive samples with circular or square cross-section obtained by pure shear. The method was originally suggested by V.M. Segal and his colleagues in the period of 1970-1980 and R. Z. Valiev contributed first of all to its further development. The objective of the method is strong deformation of the material without change of the cross-section of the sample (see Figure 2) [2-4, 6]. The ECAE method represents the process suitable especially for metal forming that is based on many times repeated operations until the total value of deformation necessary for required grain refinement is reached. Principles of design of associated operations necessary for continuous production of fine-grained metallic materials are to a large degree similar to those used in standard forming processes.

Designers have to respect the economics of production, which requires as little forming operations as possible, easy maintenance of tools and proper selection of material for dies and additional equipment. The original design of the ECAE method exhibits some limitations, such as relatively short length of a processed piece. This implies discontinuity of the process, its low efficiency and high costs. In addition, both ends of extrusion billet include usually non-uniform structure with microcracks and thus part of the extrudate has to be separated and scraped, which has also negative effect on costs.

Products produced by ECAE method exhibit higher mechanical properties and lower machinability due to refinement of material grains. For that reason, the objective is to find a methodology of assessment of surface texture of products produced by the ECAE method and mutual relation between material grain size and surface texture should be defined. In order to preserve the characteristics on the surface of refined-grain material, studied surfaces were created without thermal influence using abrasive water jet (AWJ).

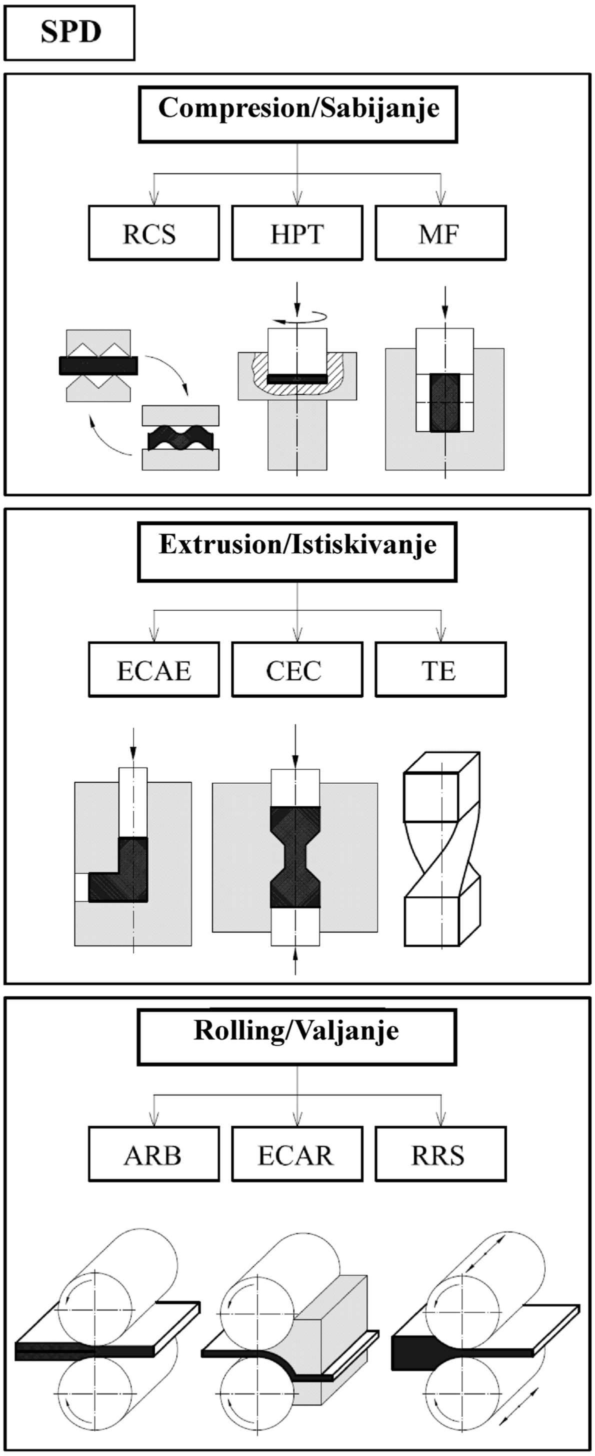

Figure 1. Classification of methods for generation of extreme plastic deformation [1-2]

Slika 1. Podjela metoda za postizanje ekstremne plastične deformacije [1-2]

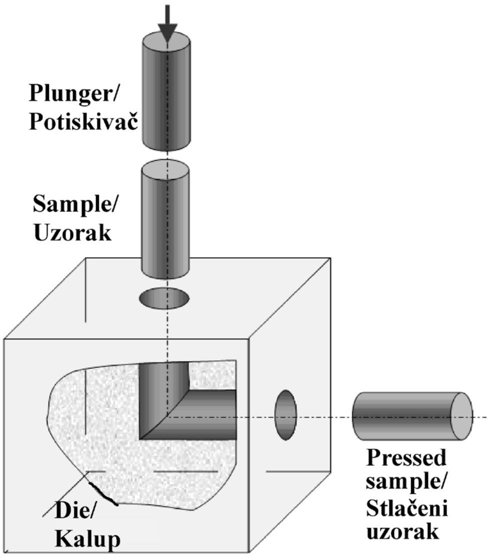

Figure 2. Principle of equal channel angular extrusion (ECAE)

Slika 2. Princip kanalno kutne ekstruzije (ECAE)

3. Experimental set up

Copper bars of commercial purity with square cross-section 35 mm × 35 mm and length of 100 mm were used as the original material for experiments of intense plastic deformation by means of ECAE method. Chemical properties of used copper are given in Table 1. Cylindrical samples with diameter of 12 mm and length 60 mm were prepared from the original material. The samples were annealed at 870 °C for 3 hours to obtain better mechanical properties and higher homogeneity of the material. Subsequently, samples were processed by ECAE method using device schematically shown in Figure 3 [5]. The die was designed by the staff of Department of forming materials, FMMI, VŠB-TU Ostrava.

Table 1. Chemical composition of Cu CSN 42 3005

Tablica 1. Kemijski sastav Cu CSN 42 3005

Cu	**Sn**	**As**	**O**	**Pb**
min. 99,5 %	max. 0,15 %	max. 0,10 %	max. 0,10 %	max. 0,10 %
Sb	**Al**	**Fe**	**Se + Te**	**Bi**
max. 0,08 %	max. 0,05 %	max. 0,05 %	max. 0,03 %	max. 0,01 %

The angle between the channels of the ECAE die was 105° (Figure 3). The substance HP 517 was used for channel lubrication. Deformation path B_C was applied during the extrusion (rotation of sample after each pass at 90° in the same direction) supplement by exchange of the front and back ends of the sample.

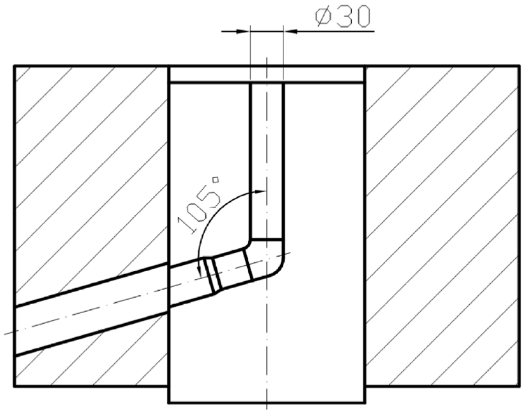

Figure 3. Scheme of used die (according to utility model CZ 18713 U1) [5]

Slika 3. Shema korištenog kalupa (sukladno uporabnom modelu CZ 18713 U1) [5]

This deformation path is generally regarded as the fastest way to achieve a homogeneous structure consisting of equiaxed grains [2]. A set of seven samples (extrusion billets) was prepared by the ECAE technology; each sample was subjected to a different number of passages through the die at temperature of 20 °C or 300 °C (see Figure 4 for details of individual samples). At the second stage of the experiment, samples created by the ECAE method were cut by AWJ at the Institute Geonics of the ASCR v.v.i. in Ostrava. Experimental conditions of AWJ cutting of extrusion billets are summarized in Table 2 and Figure 5.

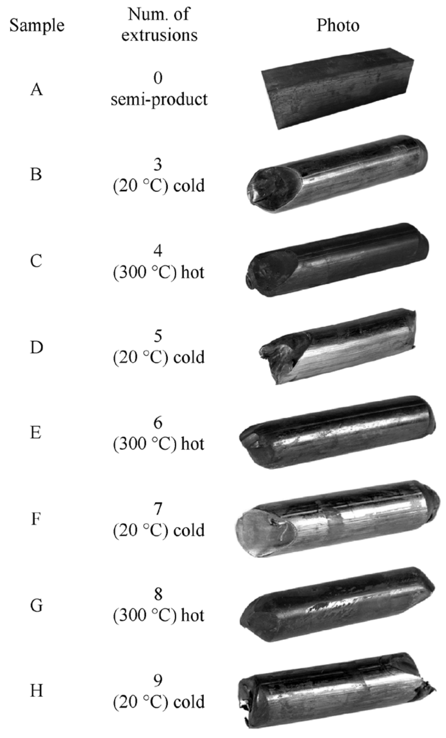

Figure 4. Summary of samples prepared by the ECAE method

Slika 4. Skup uzoraka priređenih po ECAE metodi

Table 2. Experimental condition of AWJ cutting of extrusion billets

Tablica 2. Uvjeti pokusa za AWJ rezanje ekstrudiranih bileta

Technological parameter / Tehnološki parametar	Sign / Oznaka	Unit / Jedinica	Value / Vrijednost
liquid pressure / tlak tekućine	p	MPa	370
water orifice diameter / promjer vodenog otvora	d_o	mm	0,3
focusing tube diameter / promjer fokusirane cijevi	d_a	mm	0,8
focusing tube length / duljina fokusirane cijevi	l_a	mm	76
abrasive mass flow rate / brzina abrazijskog masenog protoka	m_a	g/min	250
standoff distance / udaljenost odmaka	z	mm	2
traverse speed / poprečna brzina	v_p	mm/min	Variable / Varijable (see Figure 5 / vidi sliku 5)
abrasive size / veličina abrazije	-	MESH	80
abrasive material / materijal abrazivnog sredstva	-	-	Australian garnet GMA

As already mentioned earlier, the AWJ technology was selected due to the fact that the technology does not affect the material to be cut by any thermal load (i.e. produces so-called cold-cut), and thus the grain size influence on the surface roughness can be evaluated on surfaces created by AWJ.

Figure 5 illustrates samples created from copper extrusion billets by AWJ. As can be seen, six samples were prepared from each extrusion billet. Each sample was cut at different traverse speed $\boldsymbol{v}_p$ of cutting head. Thus, total of 48 surface areas were available for subsequent analyses.

4. Results and discussion

Metallographic sections (Figure 6) for structural analysis were prepared from the samples.

The sections were situated perpendicular to the longitudinal axis of samples. Inverted microscope for reflected light GX51 providing maximum magnification

1000× was used to study metallographic sections. Figure 6 shows metallographic sections of original material and material subjected to nine ECAE passes. Grain sizes of materials prepared by ECAE method were measured on metallographic sections to analyze the influence of grain size of material on deformation of cutting front of AWJ (i.e. on striations on the cutting surface). Measured grain sizes are summarized in Table 3.

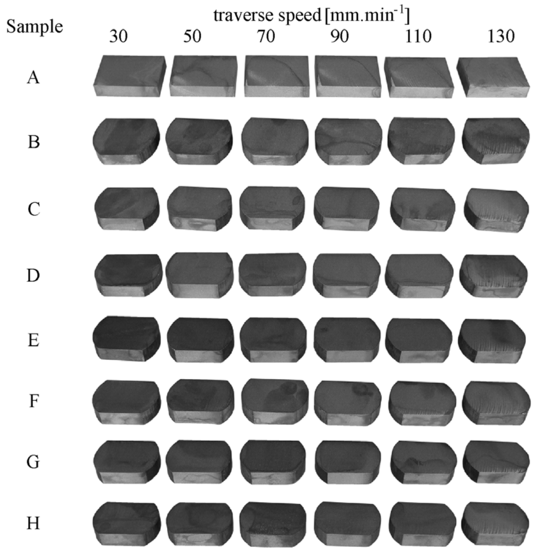

Figure 5. Samples created from copper extrusion billets by AWJ

Slika 5. Uzorci izrađeni ekstrudiranjem bileta bakra pomoću AWJ

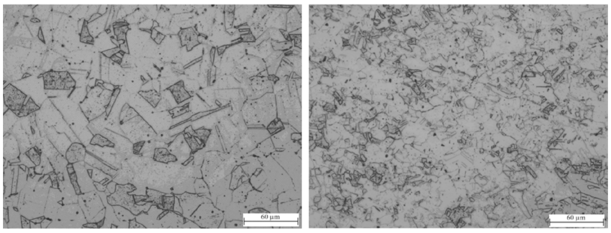

Figure 6. Metallographic sections of original material and material subjected to nine ECAE passes

Slika 6. Metalografski presjeci izvornog materijala i materijala podvrgnutog devet ECAE prolaza

Table 3. Grain sizes of materials prepared by ECAE method

Tablica 3. Veličine zrna materijala pripremljenih prema ECAE metodi

Sample / Uzorak	A	B	C	D	E	F	G	H
d, µm	19	8,8	8,7	8,1	7,3	6,9	6,7	6,5

Also hardness HV10 was measured on all samples to determine relation between number of extrusions (and thus material grain size) and hardness of material. Because material hardness depends on its mechanical properties, namely on the yield point, the Hall-Petch relation was used to relate material hardness and number of extrusions. The relationship between material grain size and the yield point is described by the Hall-Petch relation as follows:

$$\sigma_{\mathrm{y}} = \sigma_0 + k \cdot d^{-\frac{1}{2}}, \tag{1}$$

where σ_{y} is tension at the yield point, σ_0 and k are constants, and d represents grain size of the material [7-8]. The relationship is applicable in a wide area of the grains sizes up to several tens of nanometers. Therefore, dependence of hardness HV10 on $d^{-1/2}$ according to the Hall-Petch relationship was used to determine the influence of number of extrusions (material grain size) on hardness HV10 of the material (Figure 7). It is evident from the figure that hardness HV10 of the material is directly proportional to the number of extrusions.

Another important finding is the fact that the hardness of the material is also influenced by the temperature during extrusion. Material extruded at the temperature of 20 °C exhibit higher value of hardness HV10 than material with the same grain size extruded at 300 °C. The difference can be explained by reduction of deformation resistance of the material as a result of increased temperature of material.

Surfaces created by AWJ were measured by contact profilometer Hommel Tester T8000. Each sample was measured in 20 measuring traces (Figure 8). Signals containing information on distribution of surface irregularities from each trace were obtained, analysed and statistically processed.

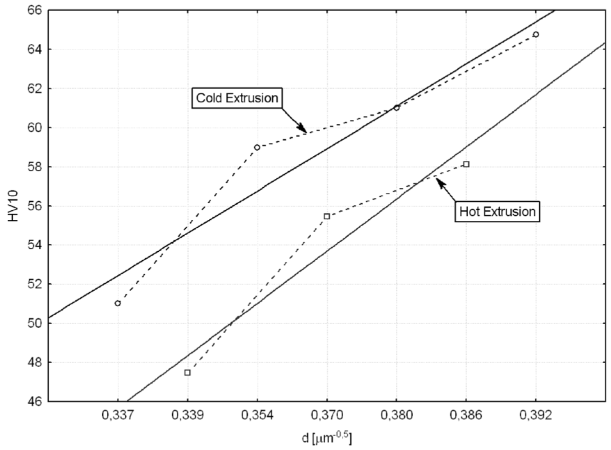

Figure 7. The dependence of hardness HV 10 on grain size $d^{-1/2}$

Slika 7. Ovisnost tvrdoće HV 10 o veličini zrna $d^{-1/2}$

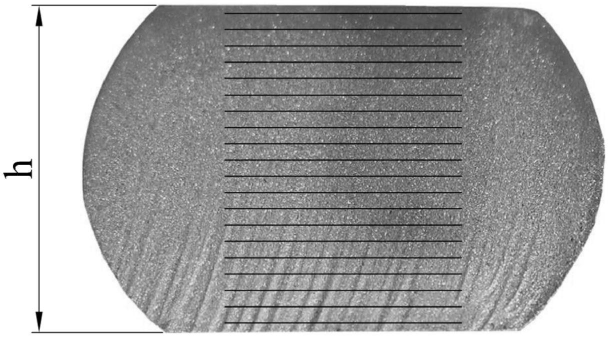

Figure 8. Photograph of surface created by AWJ with marked twenty measuring traces (v_p = 130 mm/min)

Slika 8. Fotografija površine nakon AWJ s označenih dvadeset mjernih tragova (v_p = 130 mm/min)

Measurement was performed on five consecutive fundamental lengths (l_r = 2,5 mm) and the average value of surface profile roughness *R*a was determined from the obtained data [9-10]. Figures 9 and 10 illustrate the influence of grain sizes of the material subjected to various numbers of extrusions by ECAE technology on the surface texture. As can be seen from Figures 9 and 10, the influence of grain size on the surface texture proved both for materials extruded at the temperature of 20 °C and at the temperature of 300 °C. However this effect can be observed only at the depth of cut of $h \cong 15$ mm and higher. This is due to the fact that AWJ is a flexible tool having certain kinetic energy at the nozzle exit.

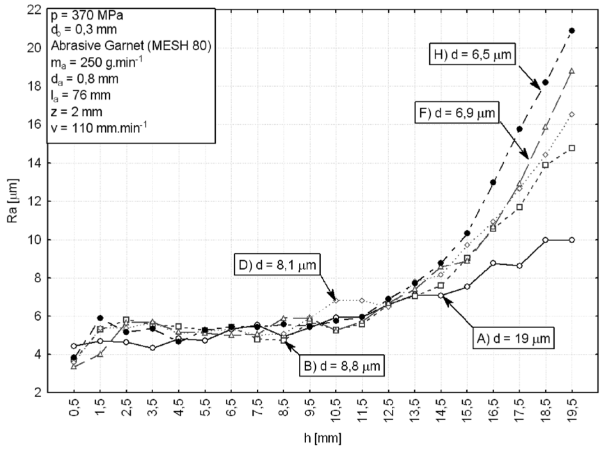

Figure 9. Dependence of surface roughness *Ra* on the depth of cut *h* for materials extruded at the temperature of 20 °C

Slika 9. Ovisnost površinske hrapavost *Ra* o dubini rezanja *h*, za ekstrudirani materijal pri temperaturi od 20 °C

The kinetic energy gradually decreases with increasing depth of cut and deformation of cutting front of AWJ can be observed. The effect occurs at the depth of cut of about 15 mm for tested material under given experimental conditions.

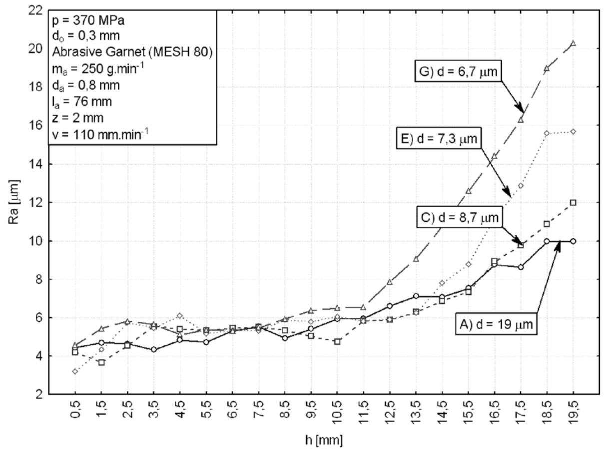

Figure 10. Dependence of surface roughness *Ra* on the depth of cut *h* for materials extruded at the temperature of 300 °C.

Slika 10. Ovisnost površinske hrapavost *Ra* o dubini rezanja *h*, za ekstrudirani materijal pri temperaturi od 300 °C.

5. Conclusions

Large plastic deformation with significant grain refinement can be obtained using ECAE technology and thus also the change in mechanical properties of materials can be observed. Original grain size of the copper with commercial purity was reduced by more than 300 % in the experiment described in the paper. Vickers hardness measurement was performed to determine changes of mechanical properties depending on the number of extrusions. The measurement proved the relationship between material grain size and its hardness. The increase of hardness between the original material and material after 9 extrusions was more than 70 %. Another important finding was the difference in increase of hardness for the materials extruded at room temperature (20 °C) and at elevated temperature (300 °C). The hardness was about 10 % lower for materials extruded at the elevated temperature compared to materials extruded at room temperature as a result of reduction of deformation resistance of the material due to its increased plasticity at higher temperature.

The influence of structural changes of the material on its machinability by AWJ technology was studied in the next part of the experiment. Parameter *R*a (mean arithmetic deviation of profile) was selected to evaluate the material machinability. A set of 48 samples was prepared using AWJ technology. The samples were measured in 20 measuring traces using contact profilometer Hommel Tester T8000. The measurement proved that the material grain size influences significantly resulting surface texture produced by AWJ cutting. Roughness *R*a of the material subjected to nine extrusions was by 100 % higher compared to that of original material. This implies reduction of the machinability of the material with increased number of extrusions by ECAE method. Individual extrusions increase the resistance of material, work and power required for the material deformation.

Acknowledgments

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