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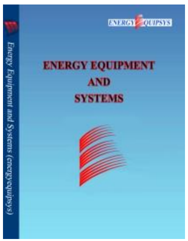

Experimental investigation of the effects of cutting parameters on machinability of ECAP-processed ultrafine-grained copper using tungsten carbide cutting tools

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ABSTRACT

The production of nanostructure materials or ultrafine grain (UFG) has been noticed by most of research society due to high strength, wear resistance, formability and high plastic strain rate. These features result from microstructure materials (100-300 nm) and unique defect (grain boundary-dislocation) make these material ideal for medical implant and structured components of aerospace and energy systems. The ways of producing UFG for these advanced engineering projects have not been considered yet. Due to the fact that nanostructured materials can show a good mechanical strength, researchers are using different ways to change pure copper into nanostructure one. One of these methods is applying process in equal channel angular pressing (ECAP), which coarse grain copper changed to nanostructure one. In this study, machinability of UFG as well as coarse grain (CG) copper is really considered in turning. To evaluate the machinability, cutting force, tool wear, chip morphology and surface roughness have been studied. Experimental results confirmed that UFG copper can be machined more efficiently than CG copper. In other words, the amount of BUE is reduced during turning ECAP copper due to the hardening of the pure sample. In comparison to CG copper, cutting force and surface roughness for UFG copper were less. As a result, machining performance can be improved partly by cold-work applying ECAP process.

Keywords: Machinability; ECAP; SPD; UFG; Surface Roughness.

1. Introduction

Nowadays , the fabrication of ultrafine grained (UFG) materials owing to their high strength, wear resistance, formability and high plastic strain-rate has been significantly noticed among the research community that can be widely used in energy equipment, aerospace and petrochemical industries [1]. Severe Plastic Deformation (SPD) is one of the most popular techniques for producing the UFG materials and improving the mechanical properties of materials regarding to grain size reduction to make these materials ideal for medical, industrial or aerospace applications [2]. The enhancement in the mechanical properties is

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due to the grain size reduction, countless dislocations and High Angle Grain Boundaries (HAGB) generated after the SPD process. Equal Channel Angular Pressing (ECAP) as one of the most efficient SPD methods has been established for fabricating relatively large billets of UFG copper from the regular coarse grain one. ECAP is one of the most suitable methods for producing the materials used in the scale of industrial applications, so this technique is a great candidate to fabricate UFG materials with high mechanical properties. As it is illustrated in Fig. 1, during the ECAP process a metal billet is mechanically pressed into an equal channel to pass the shear zone without changes in the original cross-section to produce a UFG billet with high value of plastic strain [3].

The output billets of the ECAP die are either round or square, accordingly to achieve the practical and realistic applications from ECAP-processed materials, further machining is vital to form the bulk UFG to a certain required shape. Hence, the machinability of the UFG bulk materials and also the cutting tool composition are of intense importance to be investigated and considered owing to the indispensable role of machining for finalizing the shape of the billets. The main purpose of this study is to conduct a thorough investigation on the machinability and machining parameters of copper ECAP-processed billets using the carbide cutting tools to prepare them for broad applications [1-3]. The main criteria for opting the carbide tools is their affordable cost and practical role in industry to cut the pure coarse-grained copper and its alloys in turning process. On the other hand, the polycrystalline diamond (PCD) is also a known and common cutting tool for regular coarse-grained copper in industry and can be a serious nominee for cutting the UFG copper [4]. Despite the fact that the surface finish and the wear resistance of the diamond tool is definitely superlative, but the prohibitive price of diamond tool has led to less captivation than the carbide one. It should be certainly mentioned that in some cases, the carbide tools may cause smearing and large value of cutting forces, so the diamond tools are more favorable accordingly. Whiles numerous researchers have been conducted investigations on the machinability of the regular copper with both PCD and carbide tools and discussed about the various machining parameters, but there is no document investigating on the influence of the various machining condition and parameters on the UFG copper. Although the machinability parameters for pure and UFG copper using both PCD and tungsten carbide (WC) were probed and compared previously, but the effect of each parameter on the machinability was not considered [5-8]. To satisfy this interest and to evaluate the machinability of the UFG copper comprehensively, in this study the effect of several cutting parameters (such as cutting speed, depth of cut, and feed) on cutting tool wear and surface roughness have been studied to propose an obvious sight about the most effective parameter on the machinability of the UFG copper to reach the desired properties [9,10]. As the result of this experiment, the most effective parameters of the machinability of UFG copper would be exactly recognized and by controlling these parameters while machining, the favorable and ideal surface finish of the samples would be in access with higher quality for critical applications [11-14]. Also, by controlling the aforementioned machining parameters, the surface finish quality of carbide tools can be closer to that of uncontrolled PCD tool. In the other words, recognizing the effective at first and controlling the parameters thereafter, can lead to economic prominence by proposing the higher quality of surface finish using a cheaper cutting tool [15,16].

2. Materials and setup

In this section, the considered material for the tool and the samples, the ECAP setup, the machining setup and required set parameters for undertaking the experiments are comprehensively introduced and discussed.

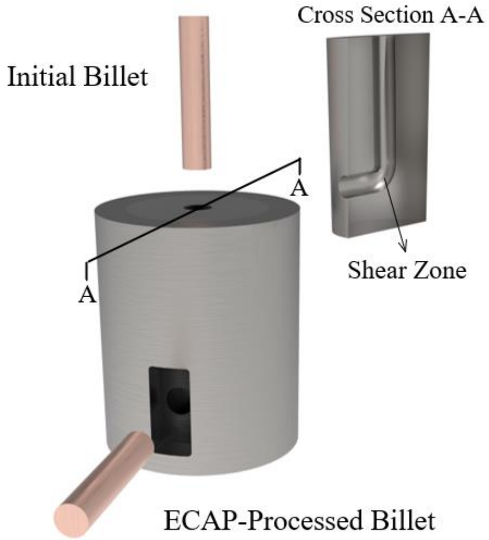


Fig. 1. Schematic representation of the ECAP process procedure

Fig. 2. The ECAP die components, a) general view, b) disassembly view

2.1. ECAP die parameters and sample material

As it is noted previously, for improving the mechanical properties of the regular copper, the samples were pressed through two constant cross-section intersecting channels to obtain UFG copper with higher mechanical properties. In this study, an ECAP die with both the die channel (φ) and outer corner angle (ψ) of 90° and the channel length of 97 mm is designed and manufactured. Generally, as it is illustrated in Fig.2, the die is made of two main parts: first, the central part that is made of hot work steel with the hardness of 55 HRC, and second, the outer part for reinforcement and preserving the central part, made of Ck45 steel with the hardness of 35 HRC.

In this study, samples were ECAP-processed up to four passes to obtain samples with higher strength, because after each pass of ECAP process, the value of plastic strain in the bulk material increases due to accumulative shear strain stored in each pass and consequently higher workability leads to finer grains and higher mechanical properties. Equation 1 gives the equivalent plastic strain stored in the sample after N passes of ECAP process:

$$\varepsilon_{eq} = {}^{N}\!/_{3}\left[2cot\left(\frac{\varphi+\psi}{2}\right)+\psi cosec\left(\frac{\varphi+\psi}{2}\right)\right] \qquad (1)$$

where, ε_{eq} is the equivalent effective plastic strain and N is the number of the process passes. Regarding to the four routine and fundamental routes between consecutive passes in ECAP processes, the common route of B_A is considered as the route pattern between passes of the process. As it is shown in Fig. 3, in the route B_A the specimen is 90° rotated in the alternative direction to be prepared for the further pass.

The chemical composition of the regular copper used in this research has been measured using energy dispersive x-ray analysis (EDAX) are illustrated in Table 1.

Owing to the ECAP die dimensions, the diameter and the length of the samples were 5,10 mm respectively, and the samples were well lubricated with MoS_2 and graphite for reducing the friction between the samples and die before pressing. The press ram used for this experiment is made of Ck45 steel with the diameter of 15.8 mm. All experiments were performed at temperature 200°C up to 4 passes. The ECAP setup containing the hydraulic press, ECAP die and billet before and after the process are shown in Fig. 4.

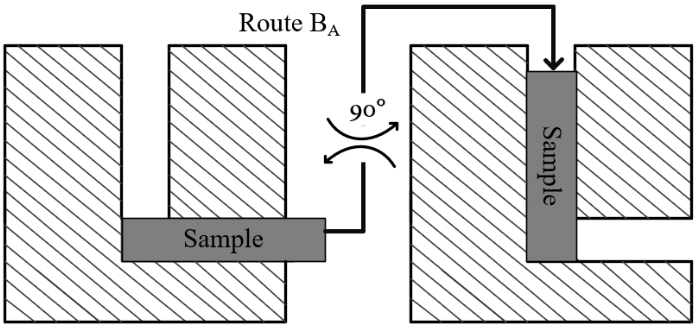


Fig. 3. Fundamental route B_A between ECAP process passes

Table 1. Chemical composition of pure copper used in the experiments

Element	Zn	Pb	Sn	P	Fe	Ni	Co	Al	S	Cu
Percentage	0.01	0.02	<0.01	<0.003	0.02	0.02	0.03	0.002	0.00	>99.5

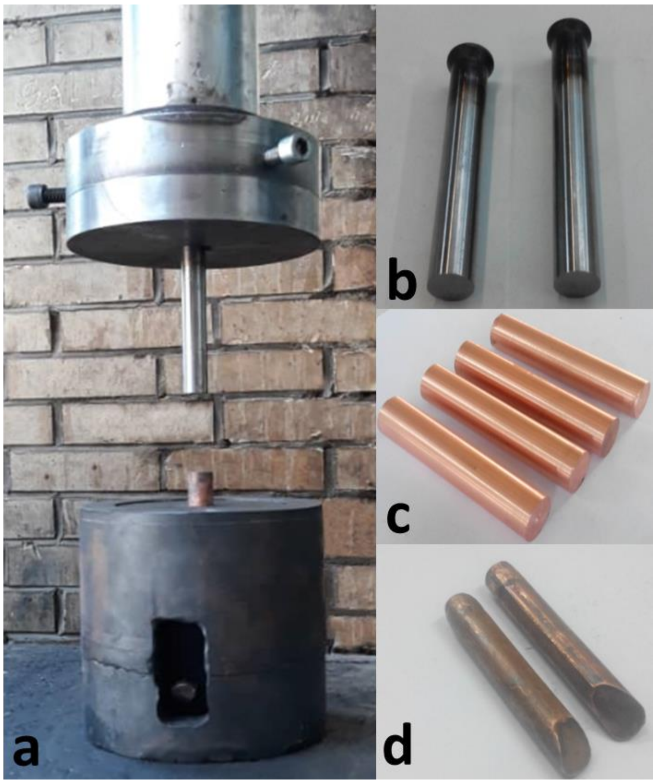


Fig. 4. ECAP process components and samples, a) hydraulic press and ECAP setup, b) press ram, c) samples before process, d) ECAP-processed samples.

2.2. Experimental procedure

As it is noted, ECAP die is used to obtain UFG billets, so five samples of ECAP-processed coppers are produced in each process pass from 1 to 4. The microstructure of the samples is investigated and analyzed using Optical Microscopy (OM). Cross section perpendicular to the extrusion axis in the middle of the samples is selected and mechanically polished to be prepared for metallography. Then the samples were etched in a solution containing 4 gr of $K_2Cr_2O_7$, 4 ml of NaCl and 8 ml of H_2SO_4. The average grain size of the microstructures was calculated using the linear intercept method. The cutting speed, feed rate and depth of cut are the three input variables of machining process. All turning experiments were conducted using a precision TN50BR lathe machine. The machining setup and conditions are shown in Fig. 5 and Table 2, respectively.

In this study a carbide cutting tool is chosen and investigated using SANDVIK turning tools catalogue. According to the catalogue and regarding to the pure copper as the specimen material, H13A with the major cutting edge angle of 35° VBMT160404KM is selected, because this tool material is substantially used for cutting regular copper and its alloys in industry.

To measure workpiece surface roughness, a surface roughness measuring instrument MarSurf M300 were used. According to the probability of obtaining various roughness values along the cutting region, three areas were randomly selected and the average roughness were reported. Also, the tangential cutting force, radial thrust force and axial feed force (known as components of the three-dimensional cutting forces) were measured using a Kistler 9265B dynamometer as shown in Fig. 5.

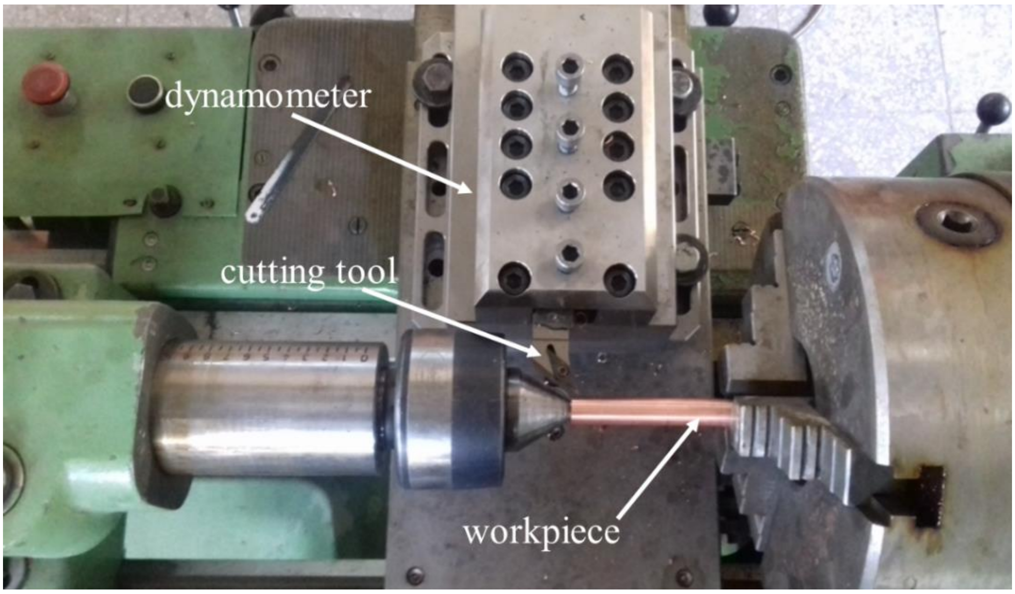


Fig. 5. Machining setup

Table 2. Machining conditions

workpiece material	Copper: coarse grain (CG), one pass ECAP processed, two passes ECAP processed, three passes ECAP processed, four passes ECAP processed
process parameters	cutting speed (V_c)= 30, 35, 40, 50, 60 m/min
	feed (f)= 0.05, 0.1, 0.15, 0.2, 0.28, 0.4, 0.48 mm/rev
	depth of cut (DOC): 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 mm
Cutting environment	dry

The Wear pattern of the tool flank surface, the value of wear and also the wear mechanism were investigated using the Scanning Electron Microscopy (SEM). Furthermore, the chip morphology and machined surfaces in various conditions were observed using a BH2-UMA Olympus digital microscope camera.

3. Results and Discussion

In this section, the results of the defined experiments are presented and comprehensively discussed. Firstly, the influence of the ECAP process on the microstructure and grain size of copper is investigated owing to its incontrovertible effect on the mechanical properties of the material. It is noteworthy to mention that the samples were ECAP-processed up to four passes to compare the machinability of UFG and pure copper more effectively. Thereafter, the effect of machining parameters such as depth of cup, cutting speed and rate of feed rate on the required cutting force, tool wear, chip morphology and surface roughness of the UFG copper at various passes of ECAP process are investigated and compared with that of coarse-grained pure copper.

3.1. The microstructure of ECPA-processed copper

The influence of ECAP process on the microstructure and grain size of the regular and ECAP-processed copper is investigated and shown in Fig. 6. These microstructures were assessed by means of Optical Microscopy (OM) for pure and UFG copper after each pass of ECAP process.

According to Fig. 6, the typical mean grain size of regular copper is 24 μm, while the grain size has been diminished remarkably after 4 passes of ECAP process due to applying severe plastic deformation. As it has been noted previously, applying plastic deformation to the coarse-grained copper would lead to the smaller grain sized microstructure. Hence, based on Hall Petch equation, the decrease of grain size would be the origin of material strengthening. The H-P empirical relationship is presented as Eq. (2):

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}} \qquad (2)$$

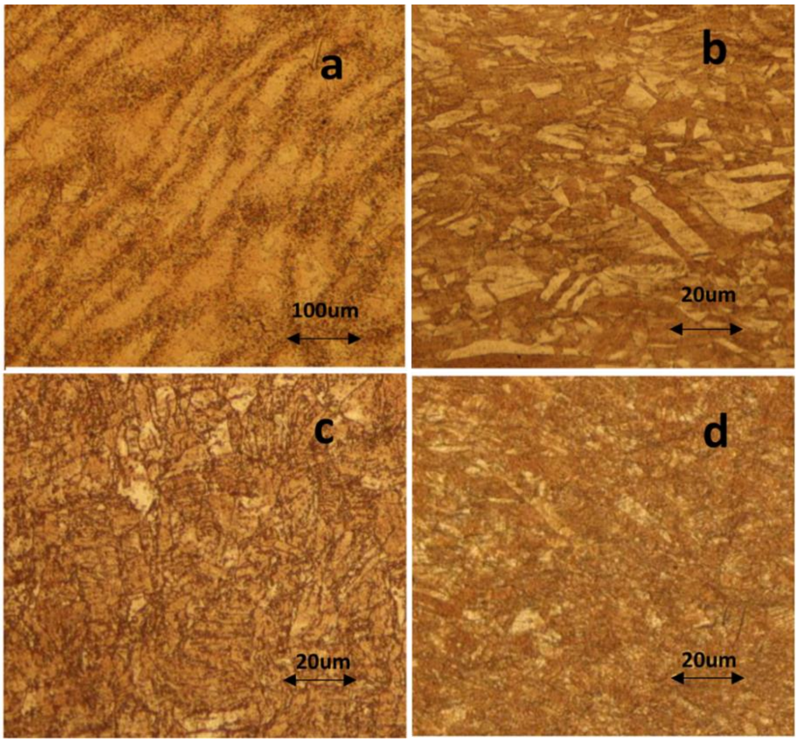


Fig. 6. Microstructure of copper samples, a) pure copper, b) after one pass of ECAP, c) after two passes of ECAP, d) after four passes of ECAP

where σ_y is the yield stress, σ_0 is material constant representing the resistance of the lattice to dislocation motion, k_y is material constant strengthening coefficient and d is the mean grain size.

On the other hand, as the number of the ECAP process passes increases, the value of accumulated plastic strain increases respectively, which brings about the smaller dislocation boundary sizes and a significant increase in the dislocation's density of the microstructure. The relation between dislocation density and material shear strength is presented in Eq. (3) as:

$$\tau = \alpha G b \sqrt{\rho} \tag{3}$$

where σ is the shear strength, α is proportionality constant, G is shear modulus, b is Burgers vector and ρ is dislocation density. According to Eq. (2), it is evident that the more the dislocation density, the higher the strength of the material is.

3.2. Effects of machining parameters on cutting force

Generally, the cutting force is not only related to the tool material and geometry, but also depends on the physical properties of the workpiece. Considering the cutting forces is of high importance owing to its fundamental role on designing the cutting tool, machine power preference and workpiece deformation parameters. Hence, the cutting force for pure and UFG copper was measured during the turning process and a summary of the cutting forces as a function of machining time at $V_c = 60\frac{m}{min}$, $DOC = 0.05mm$ and $f = 0.15\frac{mm}{rev}$ is shown in Fig. 7. As it can be seen, machining the CG copper requires up to 15 percent more cutting force compared to UFG copper, while the UFG copper has higher yield stress and hardness. This phenomenon can be justified by reason of friction diminish between the cutting tool and machining chip in the cold worked materials.

The influence of cutting speed (Vc) on the machining force for CG and UFG copper has been shown in Fig. 8a. As it is shown, by incrementation of Vc, the cutting force of all samples increased at the first and then decreased. The additive response of material till $V_c = 50\ \frac{m}{min}$ is related to the built-up edge (BUE) phenomenon that happens while machining the soft materials like copper due to the existing friction between tool and chip. As soon as reaching $V_c = 50\ \frac{m}{min}$, the temperatures of deformation zones have absolutely increased that has led to softening the BUE of tool and consequently the reduction of cutting force. On the other hand, at higher values of Vc, the flow of workpiece on the tool surface would be easier due to temperature growth, therefore the value of cutting force decreases. As the last item worth mentioning, it is seen that UFG copper requires less cutting force in contrast to regular copper because the amount of friction and the possibility of producing BUE in UFG copper has dramatically decreased. After further passes of ECAP process, it is concluded that the cutting force is slightly diminished.

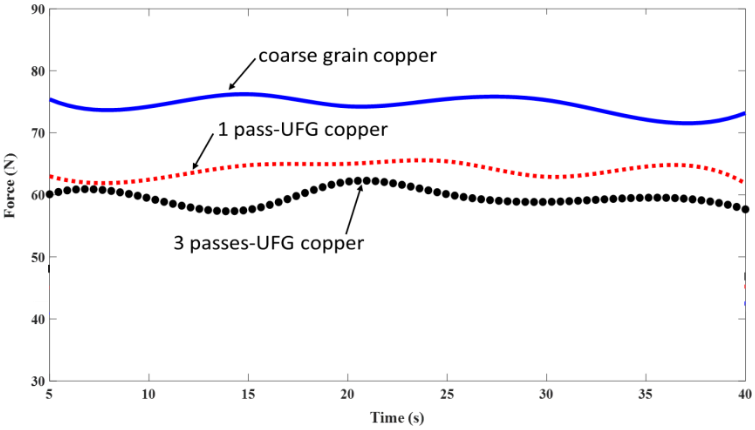


Fig. 7. Cutting force sample for pure and UFG copper during machining process with: Vc=60m/min, DOC=0.05mm, f=0.15mm/rev

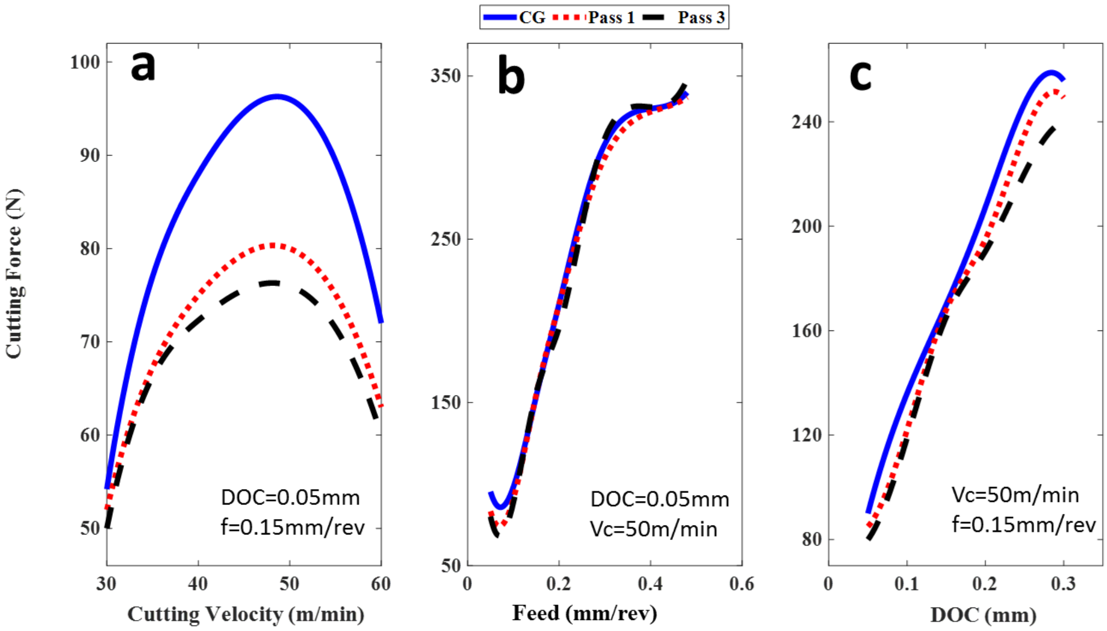


Fig.8. The effect of machining parameters on the cutting force for pure and UFG copper

The influence of various feed on the cutting force of the regular and UFG copper has been shown in Fig. 8b. According to this figure, as the feed increases, the chip cross section increases, because the workpiece resists more against shear and cutting, so the required force for material removal increases. In addition, as it is shown in Fig. 8c, by the increment of DOC, the chip volume and the deformed chip thickness are increased, so the cutting force increases consequently. Also, the cutting forces affected by feed rate and DOC show negligible alteration while comparing machining the CG and UFG copper specimens.

3.3. Effects of machining parameters on surface Roughness

Figure 9 illustrates the effects of cutting parameters on the surface roughness in turning of coarse grain and UFG processed copper. The variation of V_C causes alteration in parameters such as the temperature in cutting zone, the value of plastic deformation, the friction and the possibility of BUE formation so that each of the mentioned parameters are notably effective on the workpiece surface roughness According to the Fig. 9a, as the cutting velocity differs from 35 to 50 $\frac{m}{min}$, the roughness increases due to formation of BUE. On the other hand, as the cutting velocity reaches 50 $\frac{m}{min}$, the BUE is omitted and consequently the roughness decreases with respect to the increase of V_C. The other meaningful reason for better surface finish at $V_C > 50 \frac{m}{min}$, can also be justified by the reduction of the friction at the tool/chip/workpiece interface due to increasing cutting temperature. As another point of view, the increment of V_C leads to cutting force reduction and shear plane angle increases simultaneously, so the chip thickness would decrease as well and causing smoother surface finish. Surface morphology of the regular copper at different cutting speeds is shown in Fig. 10.

According to Fig. 9b, increasing feed has led to worse surface quality. In other words, by increasing the undeformed chip thickness, the physical contact between the tool and workpiece increases which leads to more friction and consequently more tool vibrations and finally worse surface quality.

As another perceivable result from Fig. 11 worth mentioning is the reduction of surface roughness in UFG samples. This issue can be described by the higher hardness of UFG samples against the regular one, so that the higher the hardness of workpiece is, the better surface finish would be achieved.

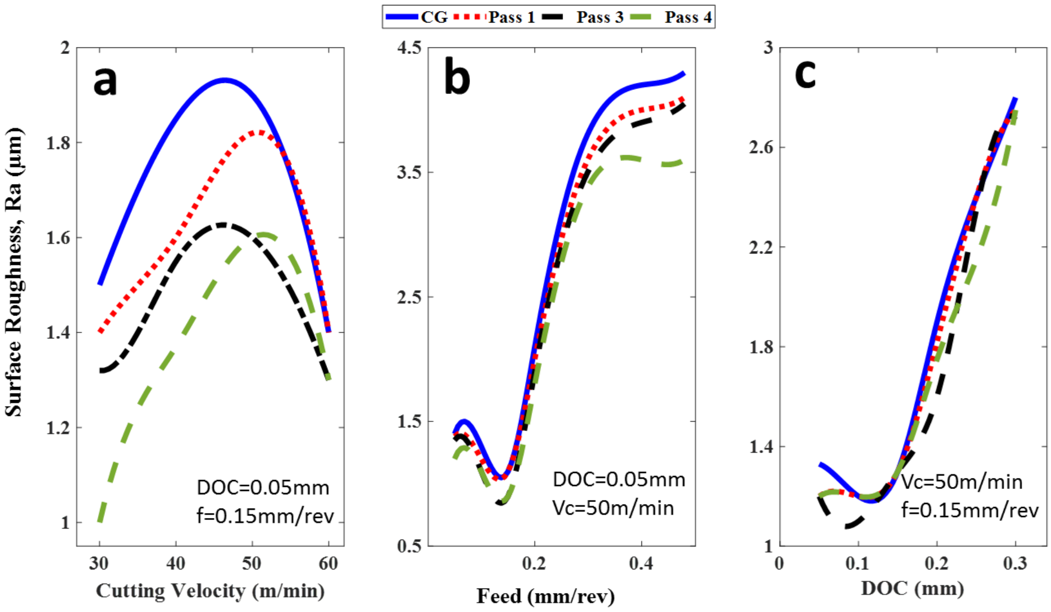


Fig. 9. The influence of machining parameters on the surface roughness while machining pure and UFG copper

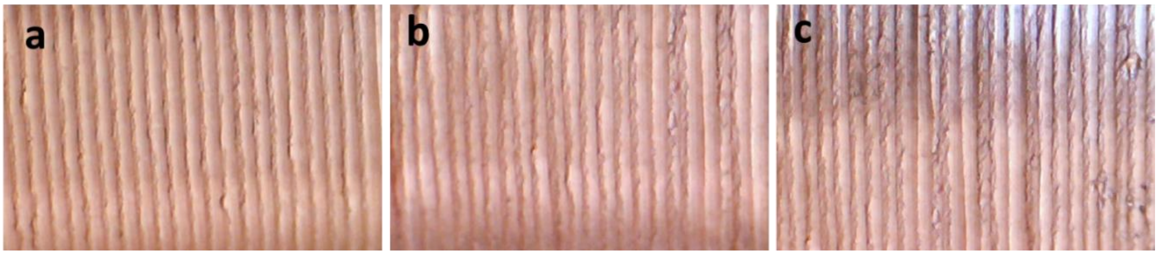


Fig. 10. The morphology of the surface of coarse-grained copper at various velocities, a. $V_C = 35\ \frac{m}{min}$, b. $V_C = 40\ \frac{m}{min}$, c. $V_C = 50\ \frac{m}{min}$

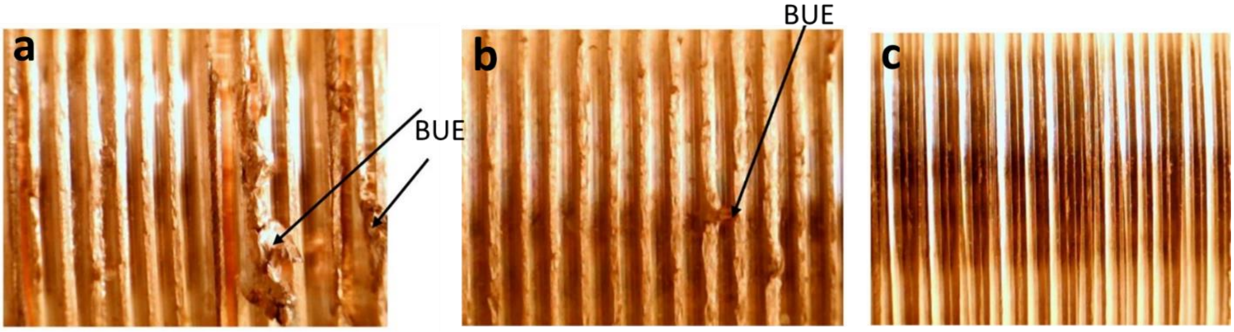


Fig. 11. The morphology of the workpiece machined surface at $f = 0.3\ \frac{mm}{rev}.V_C = 50\ \frac{m}{min}$ and $DOC = 0.15\ mm$, a. pure copper, b. one pass ECAP-processed copper, c. four pass ECAP-processed copper.

Basically, the sharper tool nose causes better machining condition, otherwise the workpiece material experiences plastic stresses leading to delay in formation of chip and finally the cutting force increases. Whenever the feed rate is less than the tool nose radius, the material gets squeezed between tool flank surface and machined surface and is exposed to high temperature and pressure close by the tool edge and flows along the uncommon transverse direction and forms side flow. In this case, cutting won`t happen properly and cause crushing that deteriorates the quality of machined surface. The workpiece surface morphology of CG copper and UFG copper were investigated at to feed rates ($f = 0.05 - 0.15\ \frac{mm}{rev}$) and the results are demonstrated in Fig. 12. According to this figure, it is observable that the side flow phenomenon occurred at $f = 0.05\ \frac{mm}{rev}$ as unremoved chips are visible on the workpiece surface causing the poor surface finish. Eventually it worth mentioning that the ECAP process had no significant influence on the side flow, because this effect is almost related to the feed rate, tool nose radius and tool wear parameters.

In addition, as indicated in Fig. 9c, increasing DOC has led to modicum roughness improvement at the first, but significant roughness incrementation has occurred in the following which was fully expected. The main reason of primary slight roughness improvement is the elimination of ploughing effect which happens in low DOC. The aforementioned phenomenon is the origin of the material non-uniform plastic flow and deteriorates the surface finish. In addition to other results, it is perceived that DOC has not perceptible impact on the surface roughness of CG and UFG copper.

3.4. Tool Wear

As it is evidently indicated in Figs. 13 and 14, increasing machining parameters (cutting speed, feed and depth of cut) lead to higher flank wear values. The reason of this response can be justified by the direct relation between temperature rise and flank wear value. In addition, by increasing machining power, the cutting zone temperature increases and consequently cutting tool wear will be increased. The main wear mechanism of UFG copper is both adhesion and abrasion owing to the existence of hard ultra-fined copper particles.

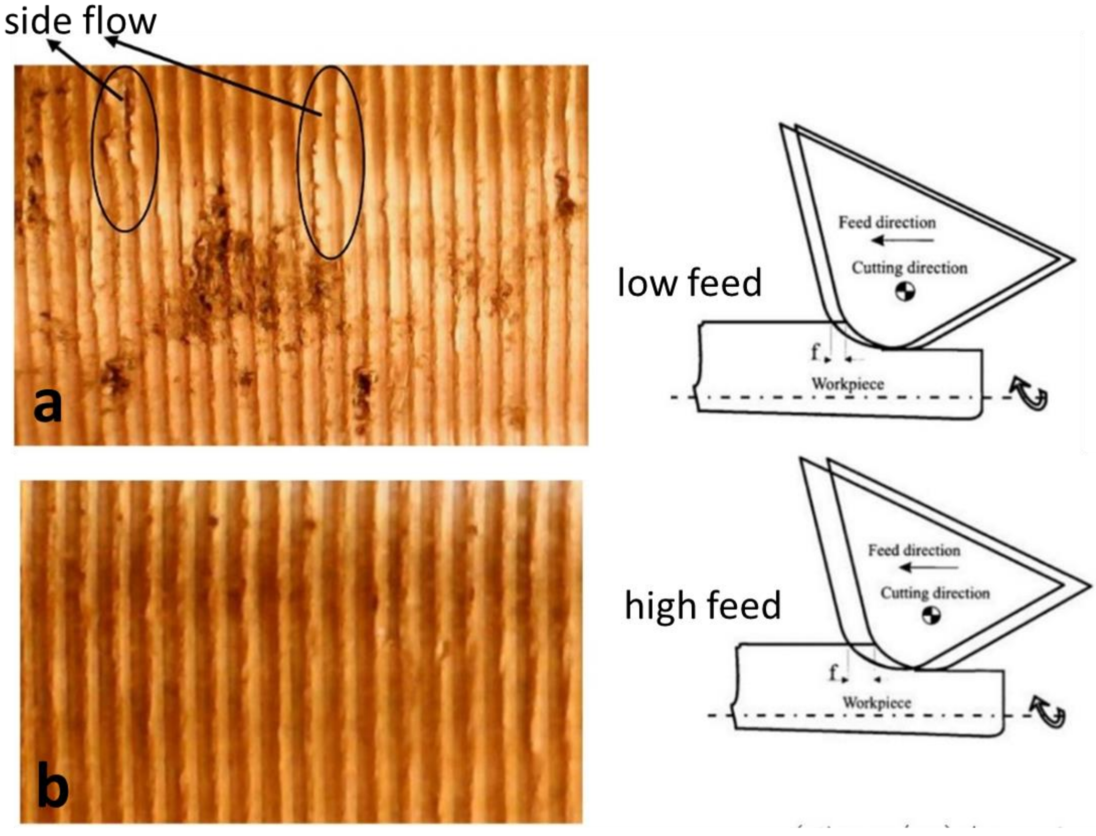


Fig. 12. The morphology of the workpiece surface at various feed rates, a. $f = 0.05\ \frac{mm}{rev}$, b. $f = 0.15\ \frac{mm}{rev}$

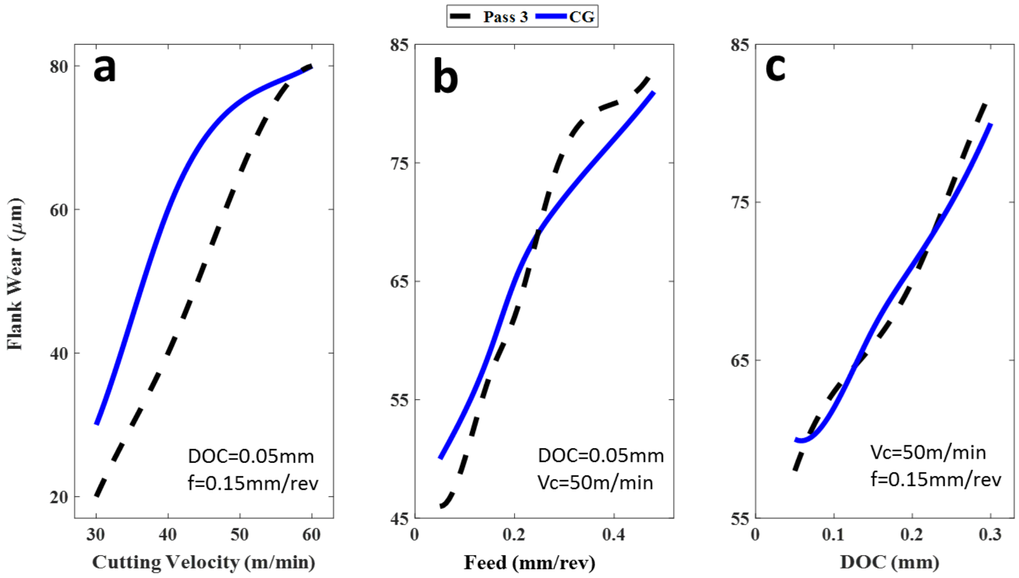


Fig. 13. The influence of machining parameters on tool flank wear while machining pure and UFG copper

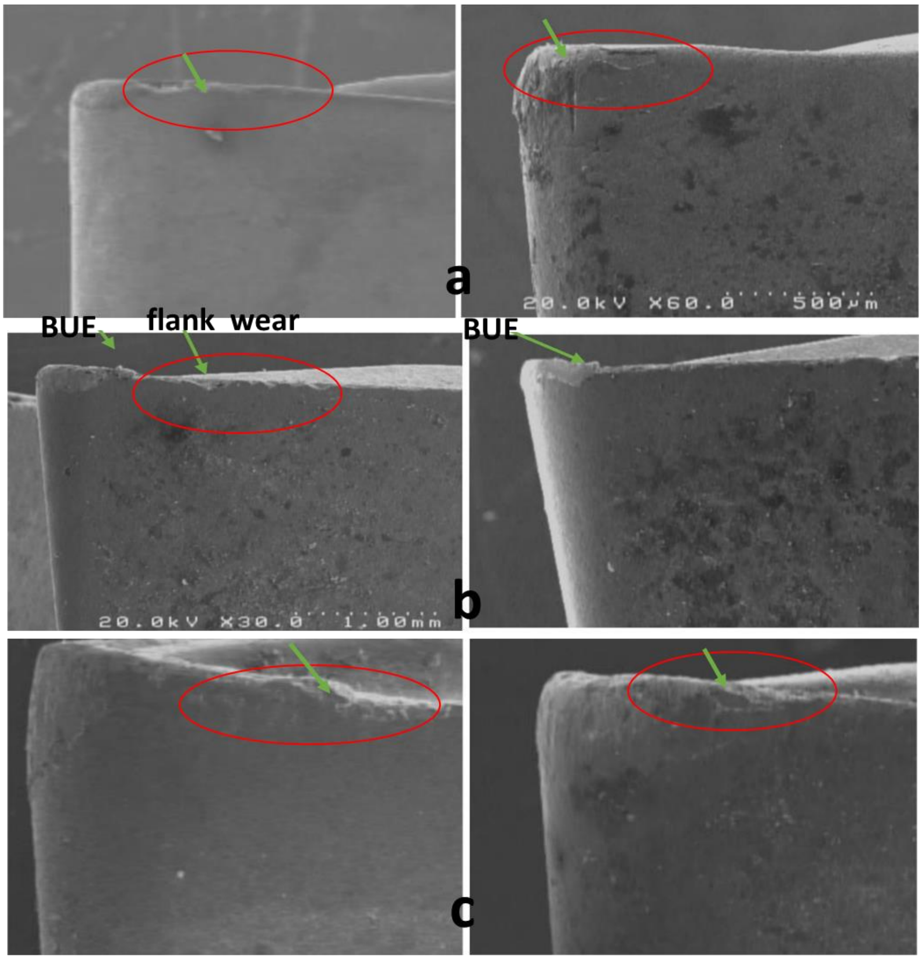


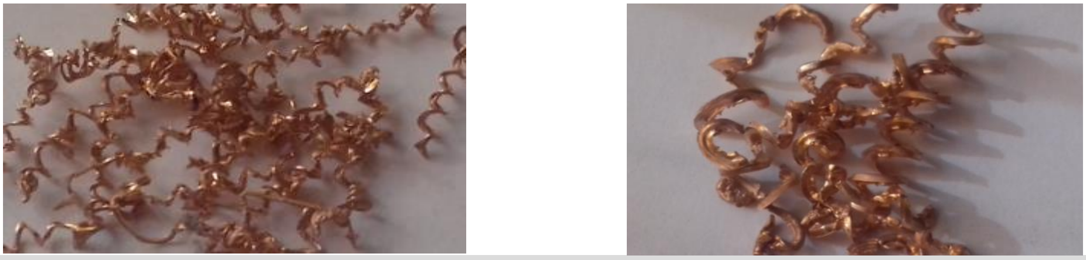
Fig. 14. Morphology of tool surface for investigating the flank wear at various cutting velocities, a) $V_C = 30\ \frac{m}{min}$, b) $V_C = 50\ \frac{m}{min}$, c) $V_C = 60\ \frac{m}{min}$

3.5. Chip Morphology

Under different machining conditions, different chip forms are formed (Figs. 15 and 16). It is obvious that long chips, like ribbon chips, snarled chips and flat helical chips, are disadvantageous and can endanger persons, tools, workpieces and the machine tool. Short chips, like discontinuous chips and spiral chip segments, can cause problems in the transport from the material separation zone or if the operator is not adequately protected. Spiral chips and helical chip segments are most favorable. The formation of the different chip forms depends greatly on the friction conditions in the contact area between the chip and the rake face, the cutting parameters and the material properties. The feed influences the chip compression ratio, i.e., the chip thickness, and thus the chip deformability. Therefore, the chip forms highly depend on the feed. The cutting speed has an essential influence on the temperatures in the chip formation zone due to heat conduction and convection. Higher cutting speeds lead to higher chip formation temperatures. Chip side flow phenomenon observed normally in high temperature region. It is noticed that in high temperature region, machining became easier due to thermal softening. But due to the strain hardening in ECAP processes, hardness in both surface and sub-surface region of UFG copper might be enhanced. For this reason, machining became difficult for materials which were forced to move in perpendicular way to feed leads to the side flow. Chips with least serrations are observed in ECAP processed condition. Machining performance was enhanced when machining was accomplished with fine grain copper structure conditions. Drastic change in terms of chip serration diminishment was observed.

f	Vc	DOC	f	Vc	DOC
$0.1\,\frac{mm}{rev}$	$60\,\frac{m}{min}$	1.5 mm	$0.1\,\frac{mm}{rev}$	$60\,\frac{m}{min}$	0.05 mm

f	Vc	DOC	f	Vc	DOC
$0.05\,\frac{mm}{rev}$	$50\,\frac{m}{min}$	0.1 mm	$0.1\,\frac{mm}{rev}$	$50\,\frac{m}{min}$	0.1 mm



f	Vc	DOC	f	Vc	DOC
$0.2\,\frac{mm}{rev}$	$40\,\frac{m}{min}$	0.2 mm	$0.2\,\frac{mm}{rev}$	$40\,\frac{m}{min}$	0.3 mm

Fig. 15. The chip morphology of UFG and pure copper under various feed, cutting velocity and DOCs.

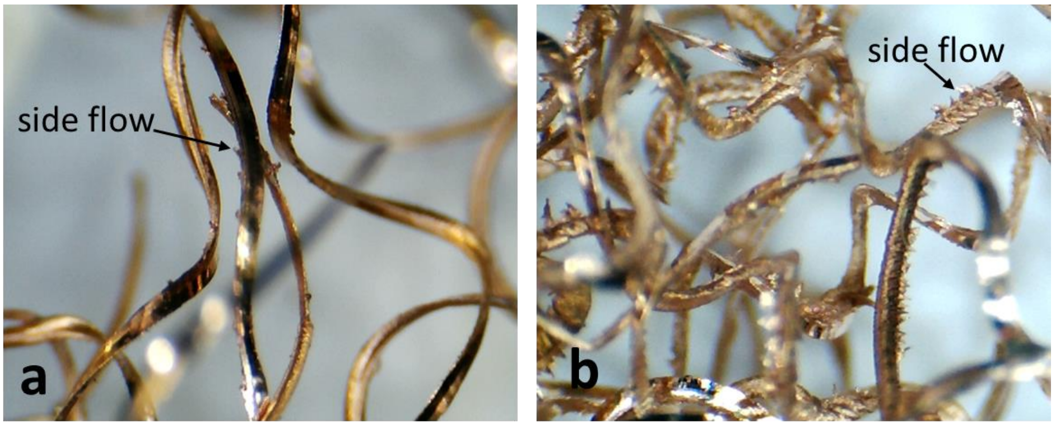


Fig. 16. The side flow influence on the formation of chip at low feeds, a) $f = 0.1\ mm$, b) $f = 0.05\ mm$

As it has been mentioned formerly, the side flow effect is a plastic deformation of workpiece which leads to pushing the material in the opposite direction of the feed. According to Fig. 16, it is evident that the decrease of feed would cause the side flow deposit and material compression on the rake surface of the tool. The aforementioned phenomenon brings about the chip serration at the trailer edge and enlarges the surface roughness of the workpiece. Besides the feed, the tool wear also affects the side flow creation and consequently the surface quality would be impressed.

4. Conclusion

This study is generally conducting a thorough investigation on the machinability of ECAP-processed copper bars and has presented a comprehensive discussion in this field, comparing the CG and UFG copper bars to pave a new avenue for machining the SPD-processed samples. The UFG copper samples were ECAP-processed up to 4 passes. The main results of this study can be summarized as follows:

1. The UFG copper bars required less cutting force for machining rather than those of CG ones meaning that the experimental results confirmed that UFG copper can be machined more efficiently.
2. In terms of surface roughness, the surface quality of UFG copper is much better owing to reduced amount of formed BUE during the machining process.
3. The tool wear increases while machining the UFG copper due to hardening of the regular bar. However, the wear mechanism in both CG and UFG samples is flank wear, but the wear pattern in CG copper is adhesive, and in UFG copper is both adhesive and abrasive simultaneously.
4. According to the obtained results in this study, ECAP process reduces the problems associated with the machining of copper, and it improves the technical and economic aspects of machining copper (machinability enhancement).

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