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Experimental study on the influence of copper oxide nano-fluid on surface integrity in turning of AISI O1 steel

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Turning operation is one of the most used operations at various industries and obtaining desired machined surface quality is one of the important concerns of researchers. In this investigation the effects of using copper oxide nano-fluid as compared with conventional fluid (soluble oil) as coolant and lubricant on surface integrity of machined surface of heat treated cold work tool steel (AISI O1) as workpiece has been investigated. So cutting speed and tool's feed rate have been considered as input variables and surface roughness, created white layer thickness and density of generated surface cracks have been considered as output parameters and regarding full factorial method of design of experiments a set of experiments for each kind of coolants has been designed and performed. The results have been shown that adding copper oxide nano particles as equal as 1% in volume to deionized water as base fluid decreases the amount of machined surface roughness as compared with using soluble oil. Also using the prepared copper oxide nano-fluid decreases the amount of created white layer thickness and density of generated surface cracks on machined surfaces as compared with soluble oil.

Keywords: Turning operation, Copper oxide nano-fluid, Surface roughness, White layer thickness, Density of surface crack

1 Introduction

Industry development and the application of new methods to improve the production process, requires extensive study in various fields, including machining process. It can be said that the main purpose of production is to minimize production time, cost of production and energy[1]. In this regard, the cutting fluids play an important role and prevent metal-metal contact in metal working operations and reduce the friction between the surfaces of the tool and the workpiece by lubrication[2]. The cutting fluids separate the surfaces in contact with each other, by creating a film on the surfaces and thus reduce friction and wear[3]. The cooling ability of cutting fluids helps to control the temperature of the tool, the workpiece and the chip. On the other hand, the cutting fluids can wash and remove the generated chips. Also, application of cutting fluids can be useful in increasing the tool life and corrosion resistance, and in decreasing energy consumption of machine[4].

In order to increase the machining performance, various methods for controlling environmental pollution have been developed, including the minimum quantity lubrication (MQL)[5], cryogenic cooling[6], emulsion cooling[7], and solid lubrication[8]. The method of coolant deliver to the cutting location and the nozzle position is as important as cooling and the cooling technique[7].

Today, the use of nano-technology in various sciences and industries has generated many advances in various fields. In the field of machining, nano-technology has also been introduced in the form of cutting nano-fluids and coated tools with nano-particles.

Cutting nano-fluids are prepared by distributing solid nano-particles in base fluids such as water, oil and ethylene glycol. In this method, increasing thermal conductivity is the main idea for improving the heat transfer ability of cutting fluid. The thermal conductivity of solid particles is greater than the fluid. For example, thermal conductivity of copper is approximately 700 times more than water and 3000 times more than engine oil, at ambient temperature [9, 10].

Suspended nano-particles have a significant effect on the base fluid's thermal properties. In recent years, many studies have been carried out on the thermal properties of nano-fluids, and almost all of them have confirmed the benefits of using them[11, 12]. The presence of nano-particles in the base fluid increases the thermal conductivity, the heat transfer coefficient and the viscosity of cutting fluids[13].

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Turning is one of the main operations of the manufacturing industries[14]. These operations are used to make cylindrical parts such as shafts, pins and screws. Due to the direct contact of the tool and the workpiece in this process, the generated heat in this process is so much[15]. Usually, at lower cutting speeds, regarding the generation of high friction, the use of lubricants and at higher cutting speeds, due to the generation of high amount of heat, the use of coolant is essential.

Sarhan *et al.*[16], used two types of lubricants, mineral oils and cutting nano-fluid (prepared by adding SiO_2 nano-particles to base fluid (mineral oil) as much as 0.2% in weight) in milling process. According to their results, a significant reduction in power consumption of machine, machining forces and special energy of machining was occured by using shear cutting nano-fluid. Vasu and Reddy[17], studied the machining ability of Inconel alloy in different lubrication conditions including dry, minimum quantity lubrication and using cutting nano-fluid (Al_2O_3 nano-particles distributed in oil). They resulted that the best results in the case of machining forces, surface roughness, tool wear and temperature distribution, was obtained using cutting nano-fluid by adding Al_2O_3 nano-particles to oil as much as 6% in weight, as lubricant. Sayuti *et al.*[18], studied the milling of aerospace duralumin AL-2017-T4. According to their results, the use of cutting nano-fluid leads to better surface quality and lower machining power. They also found the optimum amount of nano-particles added to the base fluid to achieve better surface quality and lower machining power. Nam *et al.*[19], used cutting nano-fluid in the case of minimum quantity lubrication in micro drilling of the aluminum workpiece. The researchers concluded that the use of cutting nano-fluid in this process reduces the required force and torque for drilling. Nam *et al.*[20], added nano-particles of diamond to base fluid (paraffin oil and vegetable oil) and prepared cutting nano-fluid. They used the prepared cutting nano-fluid in the micro drilling process with minimum quantity lubrication and concluded that with the use of this cutting nano-fluid, the amount of required force for drilling is reduced significantly. Also, the use of paraffin oil as a base fluid is more effective than vegetable oil. Sayuti *et al.*[21], investigated the application of SiO_2 nano-particles distributed in base fluid (coconut oil), as cutting nano-fluid in the milling process. According to their results, the machining force, machined surface roughness, and the temperature of the machining area are reduced by using cutting nano-fluid. Sarafraz *et al.*[22], used carbon nano tube aqueous nano-fluid as a coolant inside the micro-channel and examined the performance of copper-made heat sink with rectangular micro-channel. They investigated the influence of heat flux, fluid flow rate and mass concentration of nano-fluid on the local and average heat transfer coefficients, fouling thermal resistance, overall thermal resistance and local (axial) temperature. They found that higher heat transfer coefficient and lower temperature profile inside the heat sink is obtained in the case of using nano-fluid in comparison with the base fluid (water). Nakhjavani *et al.*[23], produced silver nano-particles by green synthesis method using green tea leaves which is cost-effective and available and provides condition to control the average nano-particle size. According their results, the small particles have higher thermal and antimicrobial performance. Sarafraz and Hormozi[24], quantified the forced convective and nucleate flow boiling heat transfer coefficient of Al_2O_3 water based nano-fluid. Nikkhah *et al.*[25], quantified convective boiling heat transfer coefficient of spherical CuO (II) nanoparticles dispersed in water inside the vertical heat exchanger. Sarafraz *et al.*[26], compared flow boiling heat transfer coefficients of de-ionized water and copper oxide water-based nanofluids at different operating conditions. Sarafraz *et al.*[27], quantified the pool boiling heat transfer coefficient (HTC) of functionalized carbon nano-tube (FCNT) and non-functionalized carbon nano-tube (CNT).

In this research, the effects of using copper oxide cutting nano-fluid as coolant and lubricant in turning of AISI O1 cold work tool steel on machined surface integrity including surface roughness, generated white layer thickness and surface cracking density in different cutting speeds and tool's feed rate, was studied.

2 Experiments

The JCL 6050 CNC lathe machine was used to perform experiments. Figure 1 shows the used machine in this study. Some specification of the used CNC machine was according to Table 1.

The workpiece material was AISI O1 cold work tool steel which was shown at Fig. 2. The dimensions of workpiece were also shown at Fig. 2. Chemical composition of workpiece material was according to Table 2, while the workpiece hardness was 61 HRC.

The tool used in this study was a multi-layer coated diamond shape blade with Sandwich Standard of DNMG 150406-QM, Grade 4225. The blade was shown in Fig. 3, while other features of the tool are shown in Table 3.

Fig. 1 — CNC lathe machine.

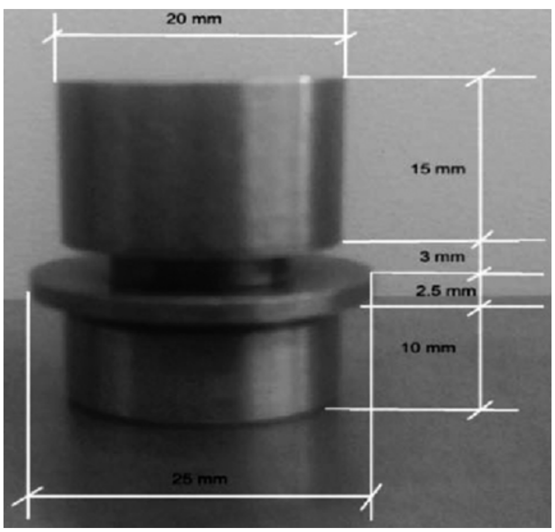

Fig. 2 — The workpiece and its dimensions.

Table 1 — Specification of CNC lathe machine.

Specification	Amount
Spindle speed range	45-3500 rpm
Spindle engine power	15 Kw
Machine weight	3200 Kg
Machine dimension	2780×1625×1948 mm

In this study, two kind of cutting fluid (soluble oil and copper oxide cutting nano-fluid) was used in order to lubrication and cooling of workpiece and tool.

In order to prepare the copper oxide cutting nano-fluid, the copper oxide nano- particles was added to the base fluid (deionized water) as suspended particles. The average diameter of nano-particles was 40 nm while their volume percent at cutting nano-fluid was 1%. In order to prevent from deposition of nano-particle and also for homogenous and uniform distribution of nano-particles, an ultrasonic device (J. P. S model, 120 watts) and a magnetic stirrer (the Alfa-HS-860 model) has been used in the preparation of cutting nano-fluid. Table 4 shows some characteristics of copper oxide nano-particles.

In this study, considering the cutting speed and tool's feed rate each one in three levels, according to Table 5, as input parameters and surface roughness, recast layer thickness and surface cracks density as output parameters, 9 tests were designed based on a full factorial method. So, for two cutting fluid types (soluble oil and copper oxide cutting nano-fluid), 18 experiments were carried out. The fixed parameters of the machining process are also given in Table 6.

In order to measure the roughness of the machined surface of samples, a Mahr Marsurf PS1 surface profilometer with 0.8 mm cut-off length and 2 mm tip radius. The machined surface roughness was measured from five different positions of the

Fig. 3 — Used blade in experiments.

Table 3 — The used tool specification.

Iso	DNMG 150604-QM
Fixing hole diameter	5.156 MM
Hand	N
Coating	MTCVD
Clearance angle major	0 deg
Insert included angle	55 deg
Grade	4225

Table 2 — Chemical composition of workpiece.

Element	Fe	C	iS	nM	rC	P	oM	S
Wt (%)	96.906	0.9	0.36	1.05	0.67	0.026	0.071	0.017

machined surface at each machining condition and their average was considered as the value of surface roughness (SR).

Scanning electron microscope (Cam Scan MV2300 model) was used to measure the created recast layer thickness on machined surface and also to measure the density of the generated surface cracks. In each sample, at five different points of the machined cross-section, the thickness of the created recast layer was measured and their average was selected as the recast layer thickness. Also in order to study the generated surface cracks on machined surface, the density surface crack which is defined as the total length of cracks (cm) in a unit area (cm^2), was used to estimate the cracking severity. For this purpose, the total length of the cracks in a 1000X magnification SEM images was measured and then this total length divided by the area of the images.

Table 4 — Characteristics of copper oxide nano-particles.

Details	Copper Oxide (CuO)
Purity	99%
Color	black
Average particle size (APS)	40 nm
Specific surface area (SSA)	~20 m^2/g
Morphology	nearly spherical
Bulk density	0.79 g/cm^3
True density	6.4 g/m^3

Table 5 — Variable input parameters and their levels.

parameters	Level 1	Level 2	Level 3
Cutting speed (V) (m/min)	30	50	70
Feed rate (F) (mm/rev)	0.08	0.1	0.12

Table 6 — Fixed parameters of machining process.

parameters	Amount
Cutting length	15 mm
Cutting fluid flow rate	20 liters per minute
Number of passes per sample	3 pass

3 Results and Discussion

In this investigation, the effects of using copper oxide cutting nano-fluid as lubricant and coolant as compared with conventional fluid (soluble oil) on machined surface roughness, recast layer thickness and density of surface cracks were studied in turning of AISI O1 cold work tool steel.

3.1 Surface Roughness

Figure 4 shows the effect of cutting speed on machined surface roughness for two types of cutting fluid at different feed rates. Regarding Fig. 4, it is observed that the surface roughness of the samples machined with copper oxide cutting nano-fluid is less

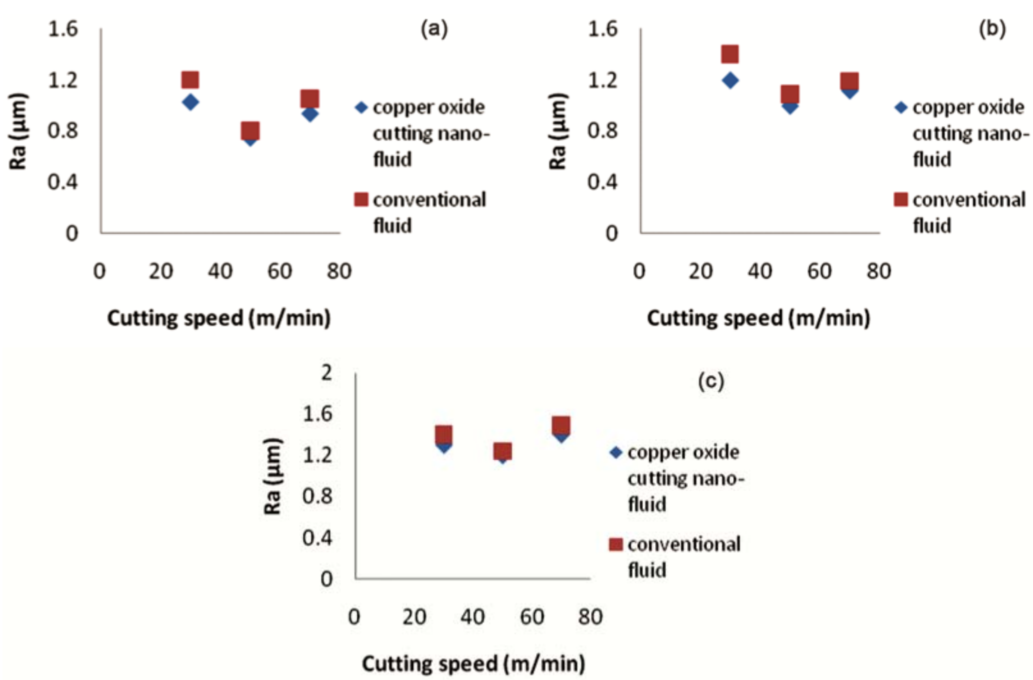

Fig. 4 — Effect of cutting speed on machined surface roughness for two types of cutting fluid (a) F= 0.08 mm/rev, (b) F= 0.1 mm/rev and (c) F= 0.12 mm/rev.

than the soluble oil. It can be explained by the high thermal conductivity and the anti-friction and anti-wear properties of copper oxide cutting nano-fluid. The copper nano-particles in the cutting fluid reduce the friction coefficient between the surface of the blade and the chip, thus improve the chip flow and reduce the probability of occurrence of the built up edge (BUE) phenomenon, which is one of the causes of increasing surface roughness[9, 10]. Also, the decrease in machined surface roughness in the case of using copper oxide cutting nano-fluid can be attributed to the reduction of the cutting region temperature due to the higher heat transfer coefficient of copper oxide cutting nano-fluid. Reducing the cutting region temperature also reduces the tool wear rate. The reduction in tool wear rate prevents from increasing of machined surface roughness induced by changing the radius and the geometry of the cutting edge (ideal surface roughness). In addition, due to the reduction of machining forces (by decreasing tool wear rate), the vibrations in the components of the machine tool and therefore the normal machined surface roughness is decreased[11].

Also, as shown in Fig. 4, the machined surface roughness decreases firstly, but then increases by increasing cutting speed in all feed rates. The relative temperature is increased by increasing the cutting speed up to 50 m/min. increasing relative temperature leads to a decrease in the hardness of the workpiece and this occurrence, improves the cutting conditions and reduces the machined surface roughness. However, with a further increase in cutting speed, the temperature of the cutting region is more increased, the temperature and the high friction between the blade and the chip leads to occurrence of the built up edge (BUE), an increase in tool wear and inappropriate chip flow, and thereby increasing the machined surface roughness. Figure 5 shows the effect of tool's feed rate on machined surface roughness for two types of cutting fluid at different cutting speeds. As shown in Fig. 5, and as previously mentioned, the surface roughness of the samples machined using copper oxide cutting nano-fluid is less than the soluble oil. Using copper oxide cutting nano-fluid leads to lower machining force and prevents from generation of built up edge on blade and reduces the tool wear and system vibrations and therefore decreases machined surface roughness, regarding the influence of nano-particles in reduction of temperature and friction coefficient in the interfaces of the tool-workpiece and tool-chip.

Also, as shown in Fig. 5, increasing tool's feed rate, leads to higher machined surface roughness. This phenomenon can be justified by Eq. (1)[9].

$$R_i = 0.0321 \times f^2/r \qquad \ldots(1)$$

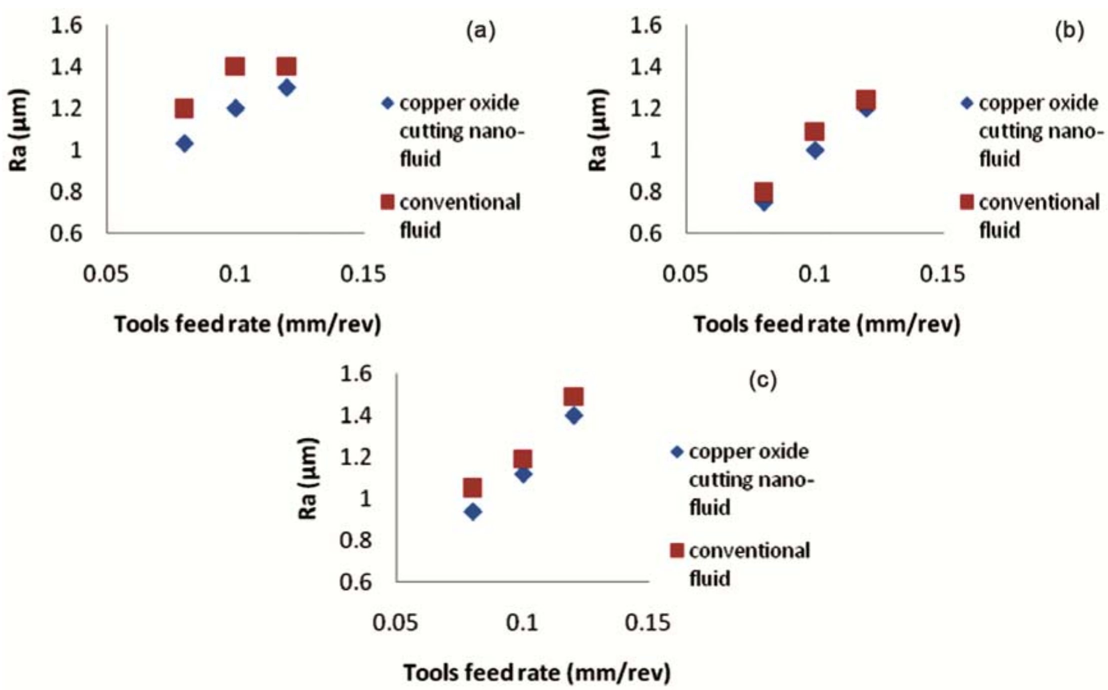

Fig. 5 — Effect of tool's feed rate on machined surface roughness for two types of cutting fluid (a) V= 30 m/min, (b) V= 50 m/min and (c) V= 70 m/min.

where, the f is feed rate, r is tool tip radius and R_i is ideal surface roughness.

3.2 Recast Layer Thickness

Figure 6 shows the effect of cutting speed on created recast layer thickness for two types of cutting fluid at various tool's feed rate, and Fig. 7, demonstrates the effect of the tool's feed rate on generated recast layer thickness for two types of cutting fluid t different cutting speeds. As shown in Figs 6 and 7, using copper oxide cutting nano-fluid leads to lower recast layer thickness as compared with

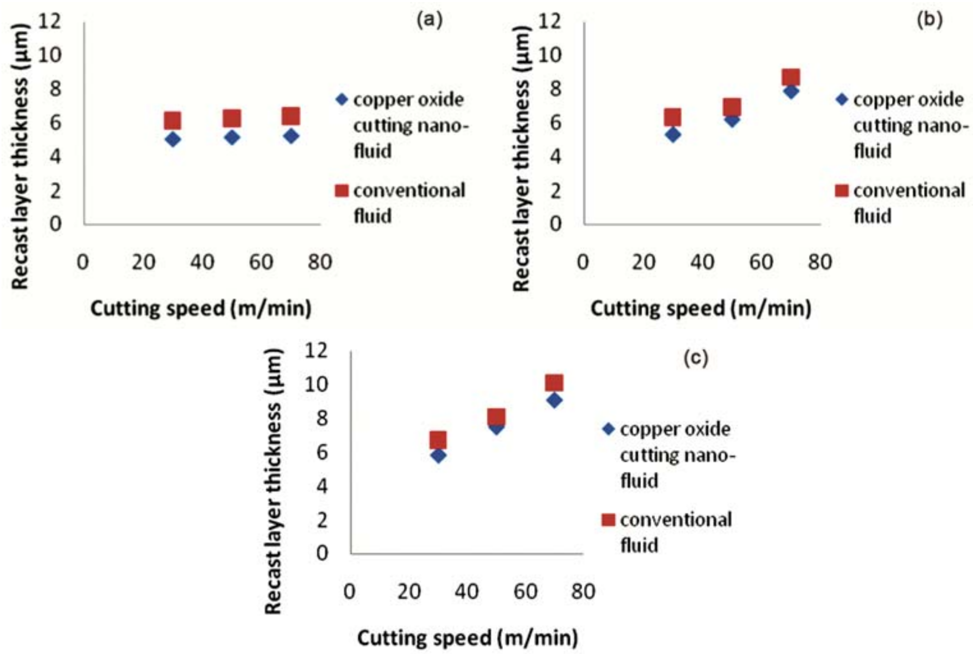

Fig. 6 — The effect of cutting speed on generated recast layer thickness for two types of cutting fluid (a) F= 0.08 mm/rev, (b) F= 0.1 mm/rev and (c) F= 0.12 mm/rev.

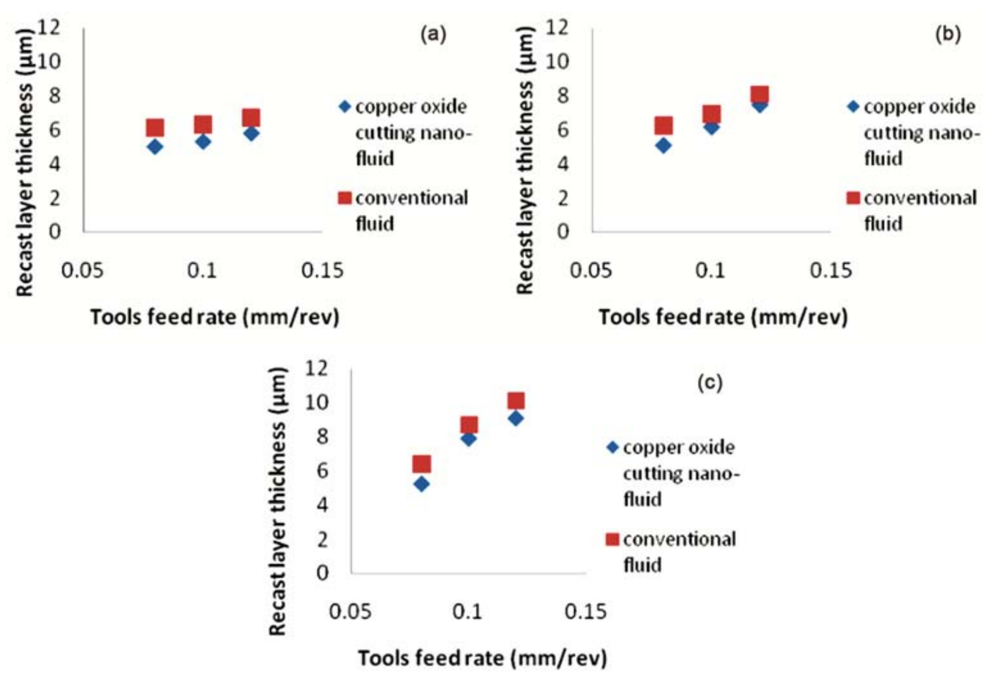

Fig. 7 — Effect of the tool's feed rate on generated recast layer thickness for two types of cutting fluid (a) V= 30 m/min, (b) V= 50 m/min and (c) V= 70 m/min.

the use of soluble oil as lubricant and coolant. Also, according to Figs 6 and 7, the generated recast layer thickness is increased by increasing cutting speed and tool's feed rate. The temperature increases in the tool-workpiece and tool-chip interfaces so that exceeds the melting temperature, by increasing cutting speed and tool's feed rate and at the end of machining process, the molten material is cooled quickly in contact with the coolant and air, and reattached on workpiece surface which increases recast layer thickness. Also the temperature of more thickness of workpiece exceeds the austenite temperature by using higher cutting speed and tool's feed rate, so the thicker recast layer is created on machined surface[10].

While, non-equilibrated freezing of molten material and generated recast layer thickness are lower in the case of using copper oxide cutting nano-fluids due to its higher heat transfer and anti-friction properties. Figure 8 and 9 are samples of SEM pictures of machined surfaces which compares the generated recast layer on machined surface in the case of using copper oxide cutting nano-fluid and soluble oil as coolant and lubricant at different machining conditions.

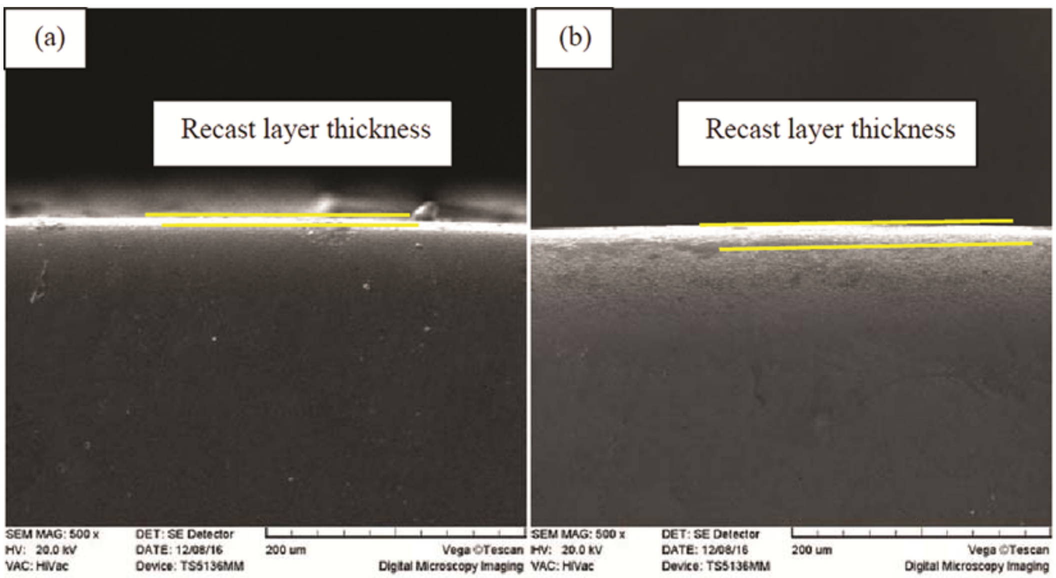

Fig. 8 — A sample of SEM pictures of machined surfaces which shows the generated recast layer on machined surface at V= 30 m/min, F= 0.12 mm/rev (a) using copper oxide cutting nano-fluid and (b) using soluble oil.

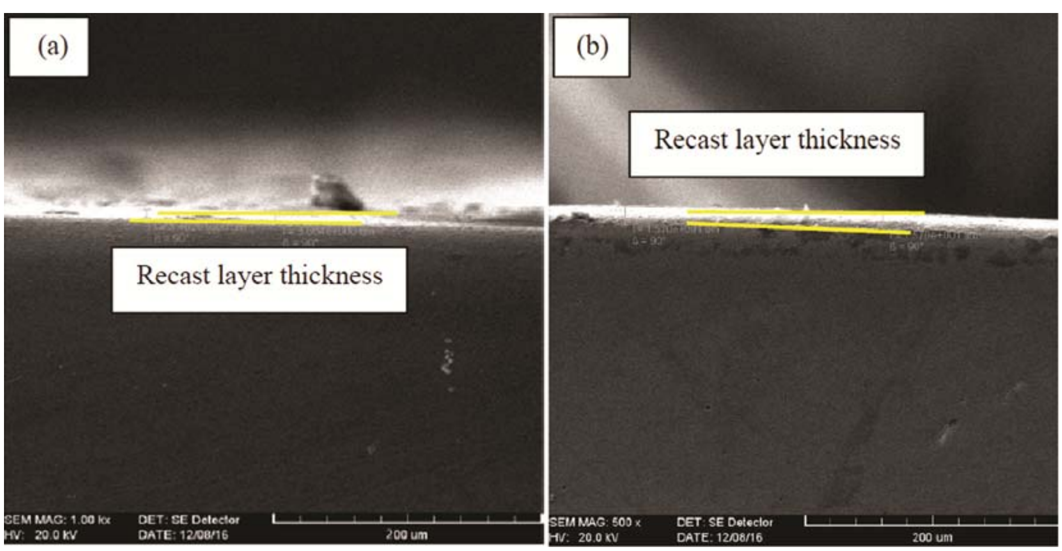

Fig. 9 — A sample of SEM pictures of machined surfaces which shows the generated recast layer on machined surface at V= 70 m/min, F= 0.08 mm/rev (a) using copper oxide cutting nano-fluid and (b) using soluble oil.

3.3 Density of Surface Cracks

Figure 10 shows the effect of cutting speed on density of created surface cracks for two types of cutting fluids at different tool's feed rates, and Fig. 11 shows the effect of tool's feed rate on the density of created surface cracks for two types of cutting fluids at different cutting speeds. As shown in Figs 10 and 11, density of created surface cracks is lower by the

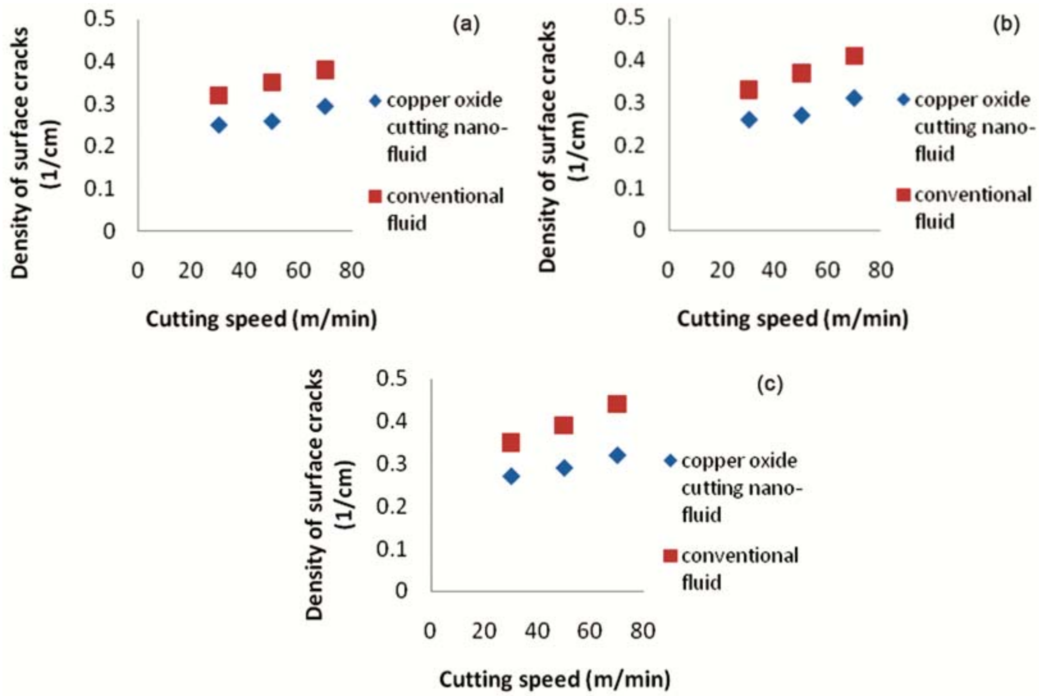

Fig. 10 — Effect of cutting speed on density of created surface cracks for two types of cutting fluids (a) F= 0.08 mm/rev, (b) F= 0.1 mm/rev and (c) F= 0.12 mm/rev.

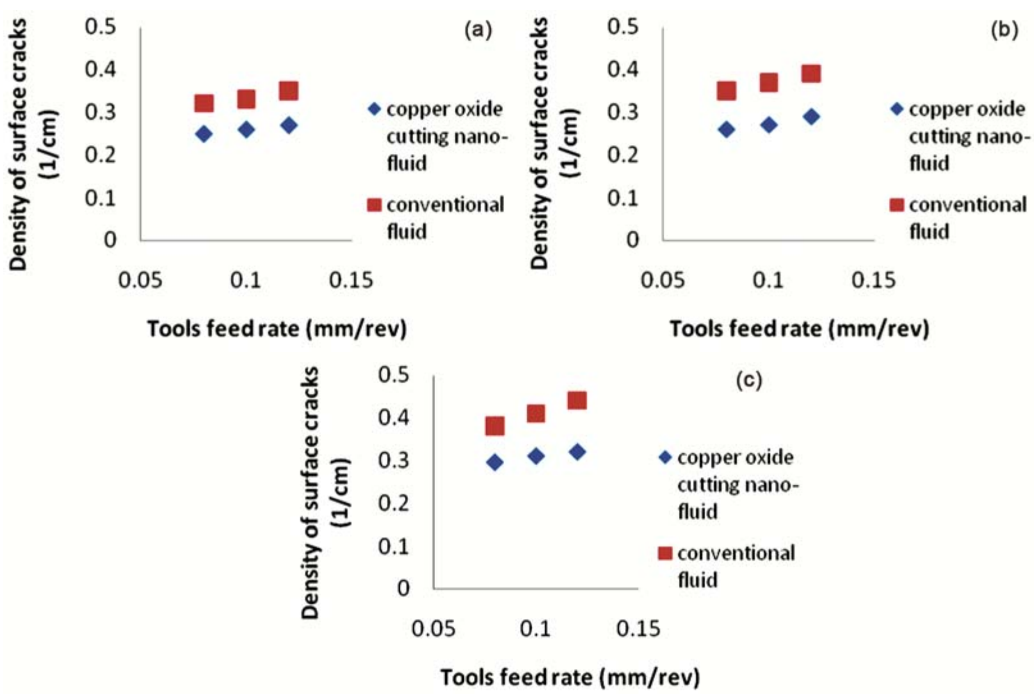

Fig. 11— Effect of tool's feed rate on the density of created surface cracks for two types of cutting fluids (a) V= 30 m/min, (b) V= 50 m/min and (c) V= 70 m/min.

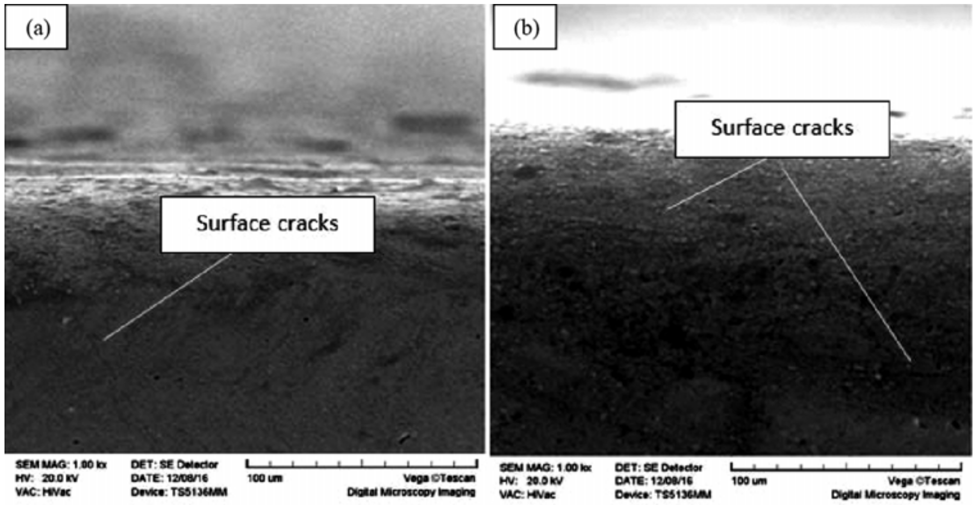

Fig. 12 —The generated surface cracks on machined surfaces at at V= 30 m/min, F= 0.08 mm/rev (a) using copper oxide cutting nano-fluid and (b) using soluble oil.

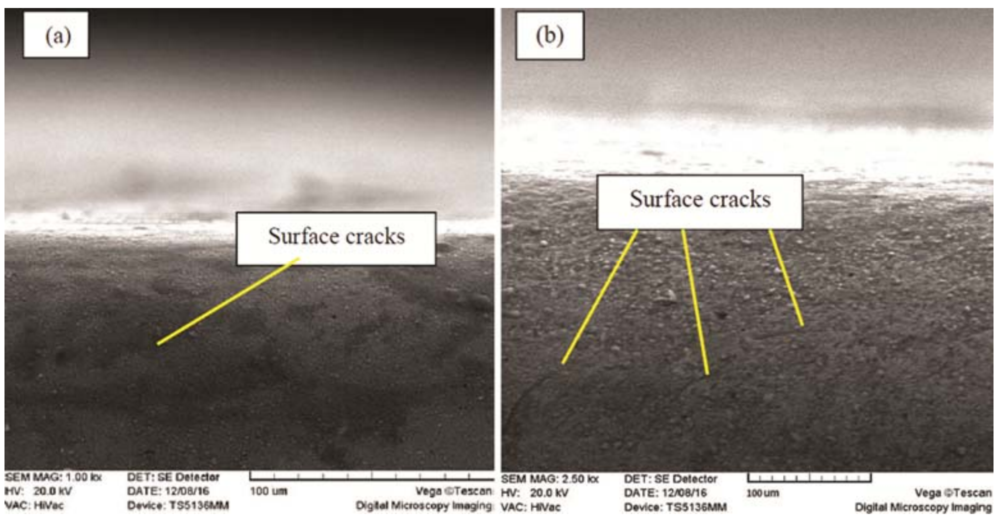

Fig. 13 — The generated surface cracks on machined surfaces at at V= 50 m/min, F= 0.1 mm/rev (a) using copper oxide cutting nano-fluid and (b) using soluble oil.

use of copper oxide cutting nano-fluid as compared with soluble oil. The molten material is cooled very quickly in contact with the air and cutting fluid and is frozen unbalanced and reattached on machined surface, which contain very high thermal stresses. If the amount of these stresses (which are tensile mostly) is higher than the failure strength of the re-frozen materials, they cause the formation of fine-grained cracks that extend to the depth of the workpiece vertically. As stated above, using copper oxide cutting nano-fluid due to its higher heat transfer and anti-friction properties, leads to lower generated recast layer thickness, lower created thermal stresses on the recast layer, resulting in a decrease in the density of the surface cracks. Figures 12 and 13, show the generated surface cracks on machined surfaces in the case of using copper oxide cutting nano-fluid and soluble oil as coolant and lubricant. Also, according to Fig. 10 and 11, the density of surface cracks is increased, relatively, by increasing cutting speed and tool's feed rate. The density of surface cracks depends to the thickness of the created recast layer, and its variation is similar to the variation of recast layer thickness[11]. The thickness of recast layer is increased by increasing cutting speed and tool's feed rate, consequently, the density of the surface cracks increases.

4 Conclusions

The results of this study showed that the use of copper oxide cutting nano-fluid as coolant and lubricant in the range of machining parameters of this research in different machining conditions of the AISI O1 cold work tool steel, improves the surface integrity of machined surface as follows:

(i) The use of copper oxide cutting nano-fluid as compared with conventional cutting fluid reduces machined surfaces roughness as much as 18.5% in average at different machining conditions.

(ii) The machined surface roughness is reduced by increasing the cutting speed up to 50 m/min, but further increasing of cutting speed, leads to higher machined surface roughness due to the occurrence of the built up edge on blade surface.

(iii) The machined surface roughness is increased by increasing tool's feed rate, in all machining conditions.

(iv) The use of copper oxide cutting nano-fluid as coolant and lubricant leads to lower recast layer thickness and density of surface cracks on machined surfaces as compared with conventional cutting fluid

(v) The recast layer thickness and density of surface cracks are increased by increasing cutting speed and tool's feed rate.

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