Journal of Modern Processes in Manufacturing and Production, Vol. 7, No. 3, Summer 2018

The Effect of Al_2O_3-MWCNT Hybrid Nanofluid on Surface Quality in Grinding of Inconel 600

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Received:June 28, 2019 ; Accepted: August 24, 2019

Abstract
Grinding is finishing process aimed at achieving surface quality and dimensional accuracy in workpieces with tight tolerances especially from materials with a high degree of hardness and strength. The grinding process of superalloys is faced with problems and challenges caused by the generation of excessiveheatas well as the adhesion of workpiecematerialon the grinding tool. Therefore, in-depth research is still under way to introduce and develop new techniques for optimization of output parameters in the grinding of superalloys. One of such techniques is to apply minimum quantity lubrication (MQL) using nanofluids.
In this research, we study the effect of using a type of mixed nanofluid comprising multiwall carbon nanotubes (MWCNT) and nano-aluminum oxide (Al_2O_3) on the surface quality in the grinding process of Inconel 600.For this purpose, the input parameters of the process are first determined. Following that, the design of experiments were performed based on full factorial method and the, grinding experiments were conducted accordingly to study the effect of various parameters including the nanoparticles size , volume concentration, and mixing ratio on surface quality of the workpiece.
Based on the results obtained from this study, while using the vegetable oil for MQL with nanofluids, the highest surface quality with Ra=0.15µm is achieved by applying a nanofluid with a mixing ratio of 75% -25% for Al2O3 -MWCNT nanoparticles, volume concentration of 0.6%, and with size of 20 nm and 15 nm for $Al_2O_3$and MWCNT nanoparticles, respectively.

Keywords
Grinding, Nanofluids, Minimum Quantity Lubrication, Surface Quality

1. Introduction

Cutting fluids and lubricants are widely used in various machining processes. Nevertheless, the consumption and disposal expenses of these materials are often not economical and they alsoharm the environment. To overcomethese issues, methods like dry machining, near-dry also known as minimum quantity (MQL) lubrication machining and using vegetable oil have drawn the attention of researchers in the recent decade. In dry machining,the flow of a compressed gas such as nitrogen is usedfor cooling the contact zone between the cutting tool and workpiece. In near-dry machining, a minimum amount of lubricant or coolant is delivered onto the tool-workpiece interface by the flow of a compressed gas which is often air [1-3].

Tawakoli et al. studied the effect of various near-dry lubrication parameters including oil flow rate, air pressure and nozzle position on the grinding force and surface roughness. According to their findings, in the near-dry grinding process, surface roughness decreases byincreasing the air pressure with an optimal value at7 bar. Their results also showed thatusing a fluid flowof100 ml/hour gives rise to a decreased surface roughness as compared with that of the fluid flow of 50 ml/h [2].

Obikawa et al. examined the near-dry lubrication in the grooving process and concluded that this method of lubrication could help reduce corner and flank wears. They also reported that the best performance in terms of minimum corner and flank wear was demonstrated by the application of MQL with an air pressure of 7 Bar and fluid flow of 7 ml/h [4].

Kalita et al. studied the use ofMoS_2nanofluidaslubricantin the grinding process. Their findings showed a reduction in the grinding specific energy when using near-dry lubrication as compared with that of wet and normal methods of lubrication. Moreover, the use of nanoparticles in the cutting fluid with a volume concentrationof 8% could significantly reduce the grinding force [5].

Sharma et al. conducted a research onmachiningthe AISI1040 steel under dry, near-dry, and wetlubricationconditionswith normal fluids. They also conducted experiments under near-dry lubrication usingAl_2O_3nanofluid. According to their results, in the near-dry lubrication with Al_2O_3nanofluid, the machining force was reduced by values of 47.8% , 29.1% , and 25.5% as compared to that of dry, near-dry, and wet lubrication conditions, respectively [6].

Maoetal. investigatedthe grinding of AISI52100 steel under four lubrication conditions includingdry, wet, MQL with normal fluid, and MQL with Al_2O_3nanofluid. They found out that the surface quality andmachining force wereimproved when applying MQL with Al_2O_3nanofluid as compared with other three conditions. [7].

Settiet al. studiedthe process measures including surface roughness and machining force in the grinding of Ti-6Al-4V superalloy using MQL with pure water, water/oil emulsion at 1:40 volume fraction, and water-based Al_2O_3nanofluid with volume concentrations of 1% and 4%. The results showed that surfaceroughness and grinding force were significantly reduced when using Al_2O_3nanofluid with a volume concentration of 4%.l [8].

Zhang et al. investigated the grinding of Inconel 718 superalloyusinganoil-based nanofluid with mixed AL_2O_3/SiC nanoparticles at different mixing ratios.According to their results, a mixing ratio of 2:1 for Al_2O_3/SiC nanoparticles produced the best results in terms of machining force and specific grinding energy [9].

Zhang et al. also studied the effect of the nanoparticles size on surface quality in the grinding of Inconel 718 using MQL with an oil-based mixed AL_2O_3/SiC nanofluid. Their findings showed that the lowest R_a (0.297 μm) was achieved when using AL_2O_3/SiC nano particles with particle sizes of 50nm and 30nm, respectively [10].

A review of the research works conducted on thenear-dry (MQL) grinding of superalloys shows that in recent years, the use of nano fluids has been studied as a technique for obtaining the desired process measures. Despite progress made in thisregard, the grinding of superalloys is faced with issues such as grinding tool wear, surface quality deficiency, and thermal residual stressin the workpiece. Therefore, further research seems necessary with the purpose of making more improvements in the process measures such as surface quality in the grinding process of advanced materials including superalloys. More studies are also required to develop new techniques for obtaining the aforesaid objective in various industries.One of such techniques is to develop and use hybrid nano fluids in the grinding process of superalloys. In this research, a new hybrid nano fluid consisting of multi-wall carbon nanotubes (MWCNTs) and nano-alumina (Al_2O_3) is introduced andits performance is investigated in the grinding process of Inconel 600superalloy. Furthermore, the effect of the process parameters including nanoparticles size, volume concentrationin the base fluid, and mixing ratio on the surface quality are studied.

2. Experimental Work

2.1 Materials

The material used for experiments, is Inconel 600 superalloycut into workpieces with dimensions of 60×20×20 mm using wire EDM. The chemical composition of the workpiece material is shown in Table 1, while its physical and mechanical properties are presented in Table 2.

Table1. Chemical composition of the workpiece material

Ni	Cr	Fe	C	Mn	Ti	Si	Al	Rest elements
73.6%	16.4%	8.4%	0.04%	0.46%	0.3%	0.3%	0.4%	0.1%

Table2. Physical and mechanical propertiesofthe workpiece material (Inconel 600)

Properties	Value
Density	8.47 g/cm^3
Melting point	1413°C
Poisson's ratio	0.3
Thermal conductivity	14.9 w/mK
Elasticity module	Gpa207

The nano particles used in this research include multi-wall carbon nanotubes (MWCNTs) and nano-alumina (Al_2O_3) supplied by US Research Company. Table 3 presents the properties of the nanoparticles.

Table3.Properties of the nanoparticles

Properties	**Nanoparticles**		
	MWCNTs	**Alpha-Al2O3**	**Gamma-Al2O3**
Purity	> 95 wt%	99+%	99+%
Outside diameter	20~30 nm	50nm	20nm
Length	~50 µm (TEM)	------	-------
Color	Black	White	White
Specific heat capacity	------	880 J/(Kg-K)	880 J/(Kg-K)
Density	~2.1 g/cm^3	3.97 g/cm^3	3.89 g/cm^3

The base fluid used for making nano fluids is LB-5000, a non-toxic and biodegradable type of oil produced by Accu-Lube Incin U.S. It is also natural-based oil and unlike hydrocarbon-based oils, is a manufactured using renewable raw material.

The magnetic surfacegrinding machine, used for grinding experiments, is supplied by JotesCo.

(Poland). The machine has a depth of cut accuracy and spindle speed of about 5 μmand 1,440 rpm, respectively. The roughness tester used for measuring the surface roughness is the DH-8 Model supplied by Diavite AG (Switzerland).
Furthermore, the MQL apparatus used in this study is the R10 model manufactured by Royal SanatCo. The apparatus creates the suction and combines the fluid with air in a venture, whereby converting the nano fluid to very small droplets and then splashing themontogrinding zone via high pressure air. The MQL apparatus has an integrated ultrasonic bath for dispersing and homogenizing of nanoparticles in the base fluid

2.2 Design of Experiment

In this research, the grinding and MQL parameters are considered as constant (Table 4). The value of these parameters were chosen based on the ranges reported in the literature [2, 5, 8].

Table4.Grinding and MQL constant parameters

Process	Constant parameter	Value
Grinding	Wheel speed(V_s)	30m/s
	Work speed(V_w)	10m/min
	Depth of cut	20μm
MQL	Nanofluidflow rate	150ml/h
	Air pressure	6bar
	Nozzle stand-off	80mm

The process parameters pertaining to the nano fluid characteristics were studied in this research. As presented in Table 5, these parameters includethe size of Al_2O_3 nanoparticles, the volume concentration of nanoparticles in the base fluid and the mixing ratio of the nanoparticles. The findings reported in the literature show that the suitable composition for the nano fluid used in MQL is obtained when particles with size of 50 nm or smaller are employed to make the nano fluid [11].Therefore, Al_2O_3 nano particles with size of 20 nm and 50 nm as well as MWCNTswith a size ranging from 20nm to 30nm were used for experiments.
The findings reported in the literature also show that the different values for nanoparticles volume concentrationhave been applied in MQL grinding with nano fluids [11]. ForAl_2O_3 nano fluids and other oxide nano-powders, volume concentration sup to 5% have been reported while for CNTs nano fluids, volume concentrations below 1% have been used. That is explained by the fact that using high volume concentrations for CNTs may increase nano fluid viscosity, cause agglomeration and prevent their effective composition in the base fluid. The volume concentration of the nanoparticles in the base fluid for the hybrid nano fluid used in this study can be calculated as follows:

$$\text{Vol }\% = \frac{(m/\rho)_{Al2O3} + (m/\rho)_{MWCNT}}{(m/\rho)_{fluid} + (m/\rho)_{Al2O3} + (m/\rho)_{MWCNT}} \quad (1)$$

Where, *m/ρ* is the ratio of the mass to density for various components of the nano fluid, including Al_2O_3nanoparticles, MWCNTs and the base fluid. Given the values for volume concentration of

NPs in the base fluid as well as the mixing ratio of Al_2O_3 to MWCNT NPs (Table 5), the weight of NPs can be calculated to synthesize the hybrid nano fluid in each experiment.

Table5.Process parameters and their corresponding values

Process parameters	Symbol	Levels	Values
Size of Al2O3NPs	A	1	20nm
		2	50nm
Volume concentration	B	1	0.2%
		2	0.6%
Mixing ratio of NPs (Al2O3-MWCNT)	C	1	25%-75%
		2	50%-50%
		3	75%-25%

In this study, MQL grinding experiments with nano fluids are conducted based on the full factorial DOE method as presented in Table 6. Two replications are considered for each experimental run, resulting in 24 MQL grinding experiments with nano fluid. Furthermore, grinding experiments under three conditions of dry, wet, and MQL with pure oilare carried out with two replications. Therefore, a total number of 30 grinding experiments are conducted in this study.

Table6. Parameters level specified by full factorial design of Experiment (DOE)

Experiment	Process parameters		
No.	A	B	C
1	2	1	2
2	1	2	3
3	2	2	2
4	1	2	2
5	1	1	1
6	2	1	1
7	1	1	2
8	1	2	1
9	2	2	1
10	2	1	3
11	1	1	3
12	2	2	3

2.3 Grinding Experiments

The Inconel 600 used as workpiece in this study is a non-ferromagnetic material,and it thus cannot be installed on the magnetic table of the surface grinding machine. Therefore, a precision vise with two T-shaped clamps along with a dial indicator was used for clamping the workpiecein the grinding experiments. For each test, dressing of the grinding wheel was performed by a carat diamond dressing tool because the aluminum in the Inconel 600compositionfills the porosities of the grinding wheel,and thereby reduces the grinding process performance.

Grinding experiments were conducted in two series. First, experiments under three conditions of dry, wet and MQL with pure oilwere carried out using the constant parameters presented in Table 4. Figure1 shows the layout for first series of grinding experiments.

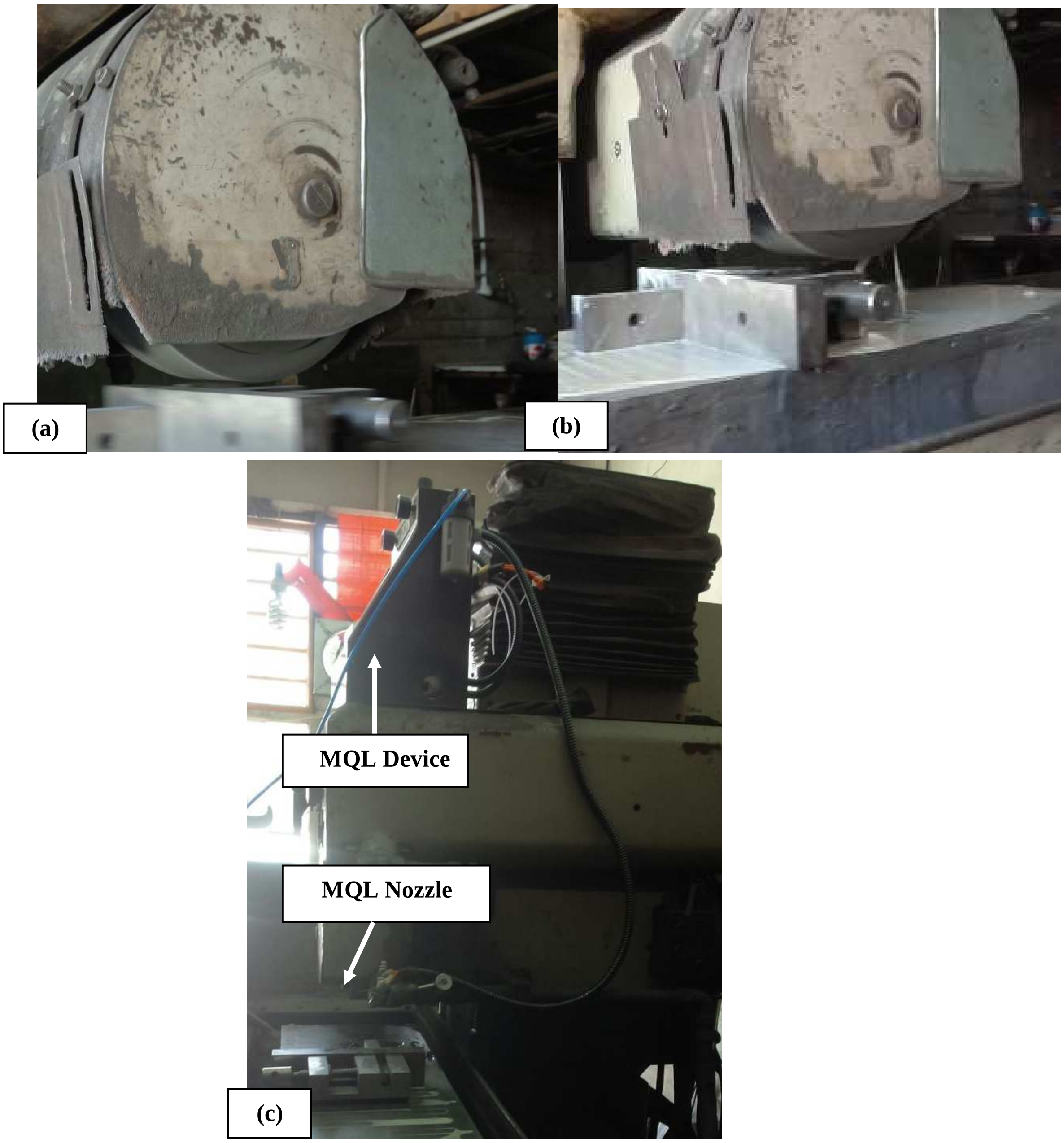

Figure1. The layout for first series of experiments: (a) dry grinding, (b) wet grinding with pure oil, (c) MQL grinding with pure oil.

In the second series of experiments, MQL grinding tests were conducted with hybrid Al_2O_3/MWCNTs nano fluids using the constant parameters presented in Table 4 as well as process parameters shown in Table 5. According to the DOE presented in Table 6, 12 nano fluids with a volume of 20 ml each were prepared. In order to fully disperse and homogenize the nanoparticles in the base fluid, each nano fluid was placed in the MQL ultrasonic bath for about 2 hours. Moreover, each nano fluid was sonicated for 30 minutes just before applying in the grinding tests. Each grinding experiment was repeated twice, after which the workpiece was released and its surface roughness (R_a) wasmeasured three times.

3. Results and Discussion

The results of surface roughness measurement for three grinding conditions of dry, wet and MQL with pure oil as well as MQL with hybrid nano fluid (HN) are presented in Table 7.

Table7.The results of surface roughness for various grinding conditions

Experiment No.	Grinding condition	R_a(µm)
-	Dry	0.622
-	Wet	0.372
-	MQL-Pure oil	0.305
1	MQL1(HN)	0.300
2	MQL2 (HN)	0.150
3	MQL3 (HN)	0.267
4	MQL4 (HN)	0.238
5	MQL5 (HN)	0.315
6	MQL6 (HN)	0.354
7	MQL7 (HN)	0.285
8	MQL8 (HN)	0.332
9	MQL9 (HN)	0.310
10	MQL10 (HN)	0.288
11	MQL11 (HN)	0.267
12	MQL12 (HN)	0.198

The bar chart of the workpiece surface roughness (R_a) for various grinding conditions based on the data presented in Table 7, are shown in Figure 2.

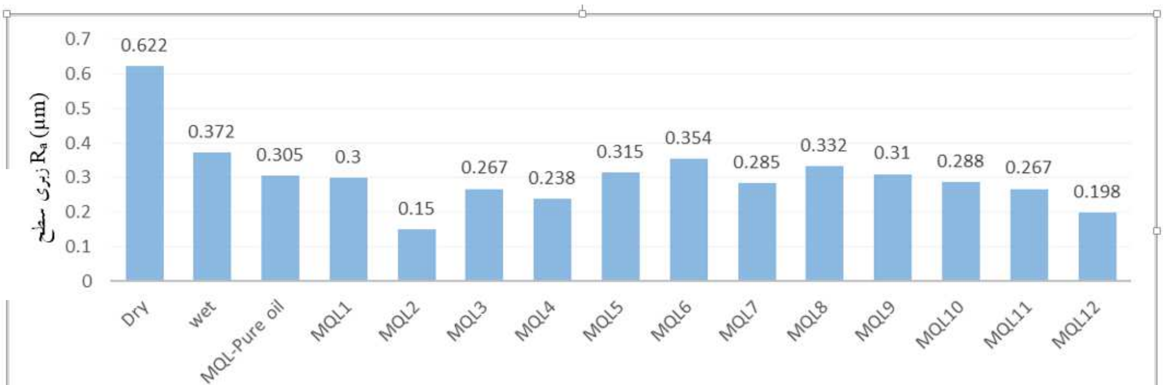

Figure2. Workpiece surface roughness for various grinding conditions

As seen in Figure 2, the maximum surface roughness (R_a= 0.622µm) is obtained in dry grinding and the minimum roughness (R_a= 0.15µm) is obtained in MQL2 grinding condition (size of Al_2O_3 NPs=20nm, volume concentration=0.6%, and mixing ratio of NPs=75%-25%).The surface roughness value for grinding in the near-dry condition with pure oil (MQL-Pure oil) is less than that of wet grinding condition using Z1 fluid.The results also show that in experiments No. 5, 6, 8 and 9, where MQL with hybrid nano fluid is applied, the surface roughness is higher as compared with that of experimentsusing MQL-Pure oil. By reviewing the results, it is clear that in all aforesaid experiments, the mixing ratio of Al_2O_3-MWCNT NPsis 25%-75%. Therefore, it can be found that an excessive increase of the MWCNT weight percentage in the hybrid nano fluid would adversely affect the quality of ground surface. This may be explained by the fact that excessive MWCNT in the hybrid nano fluid would quickly fill the pores in the grinding wheel and create built-up edge, thereby increasing the surface roughness.

Figure3illustrates the variation in mean surface roughness for various process parameters presented in Table 5.

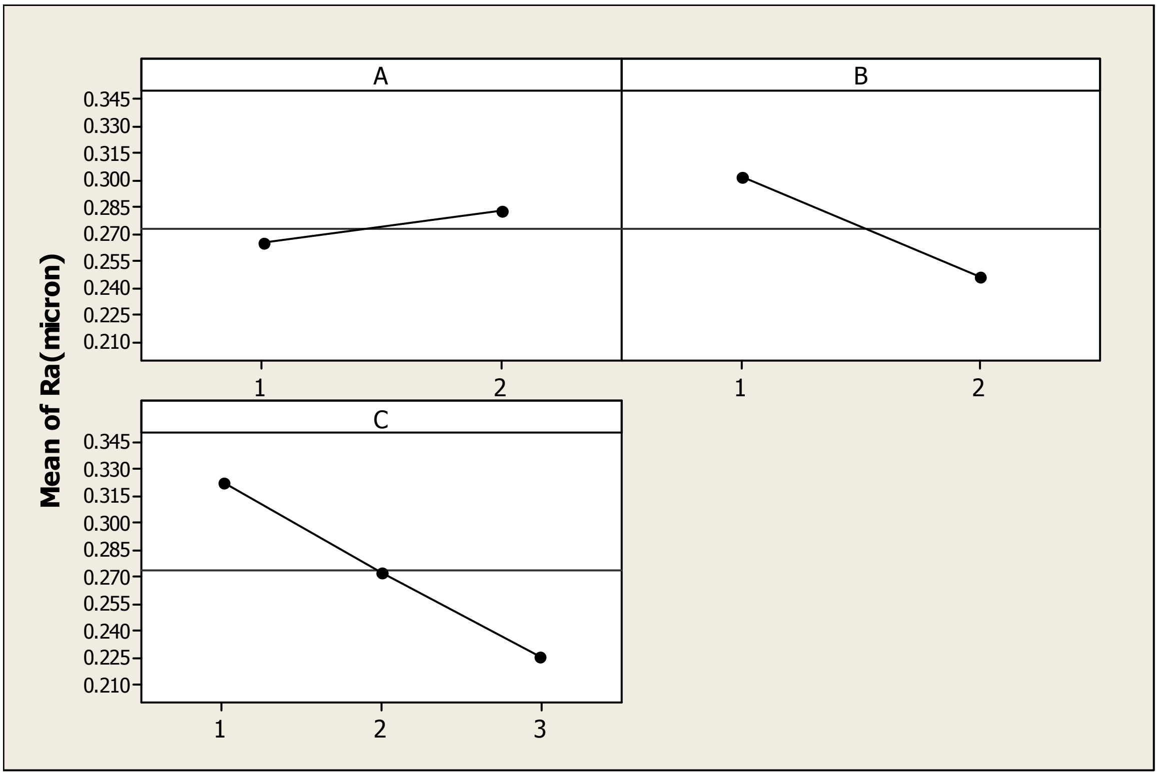

Figure3. Mean surface roughness variations as a result of changes in differentprocess parameters including: the size of Al_2O_3 NPs (A), volume concentration of NPs in the base fluid (B), and mixing ratio of Al_2O_3–MWCNT NPs (C)

It can be seen that surface roughness increases with an increased size of Al_2O_3 NPsin the hybrid nano fluid (parameter A). Using Al_2O_3NPs with size of 20nm in the hybrid nano fluid would cut less deeply as compared to that of Al_2O_3 NPs with size of 50nm, thereby producing a higher surface quality.Although the particle mesh of the grinding wheel is an influential factor on the surface roughness, the results show that the mean value of surface roughness in grinding with hybrid nano fluids is smaller as compared to that ofboth MQL grinding with pure oil and wet grinding. These resultssuggest that when Al_2O_3 NPsin the nano fluid are placed in the contact zone between the grinding tool and theworkpiece, they somehow diminish the effect of particle mesh of the grinding wheel and they evenact as a dominating factor in removing the material from the workpiece surface during the grinding process.

Figure 3 also shows that the surface roughness decreases as the volume concentration of NPs in the base fluid (parameter B) increases from 0.2% to 0.6%. The increase in the volume concentration translates to an increased number of NPs in the hybrid nano fluid, thereby yielding a higher surface quality. A further increase in the volume concentration beyond 0.6% when the mixing ratio ofAl_2O_3 –MWCNT NPs is maintained at25%-75%, would cause particles agglomeration in the hybrid nano fluid. This results in reduced nano fluid performance and consequently decreased surface quality.

As shown in Figure 3 (parameter C), the surface roughness decreasesas the mixing ratio of NPs (Al_2O_3–MWCNT) changes from 25%-75% to 75%-25%. Due to the presence of aluminum and titanium elements in the Inconel 600 structure, the former brings aboutadhesion and the latter causesthermal instability as well as heat dissipation obstruction in the grinding region, thereby leading to the formation of built-up edge and thus clogging of the grinding wheel pores. Therefore, increasing the content of Al_2O_3nanoparticles with sharp-edged shapewould help grinding wheel abrasive particles in removing the material from the workpiece and thus the grinding wheel pores take longer to be clogged. The presence of MWCNT particles is also an influential factor on increasing the heat transmission from the grinding zone. They also move into the space between the Al_2O_3nanoparticles and due to their flexibility would prevent an excessive crushing of Al_2O_3nanoparticles, thereby improving the performance of Al_2O_3nanoparticles. However, an excessive increase in the volume percentage of MWCNTs in the hybrid nano fluid would not help in reducing the surface roughness due to their flexibility.Therefore, due to their role in resolving of the built-up edge formation, the Al_2O_3abrasive nanoparticles are more effective than soft and flexible MWCNT nanoparticles in reducing the surface roughness. Figure 4 illustrates 3D diagrams of surface roughness for different parameters.

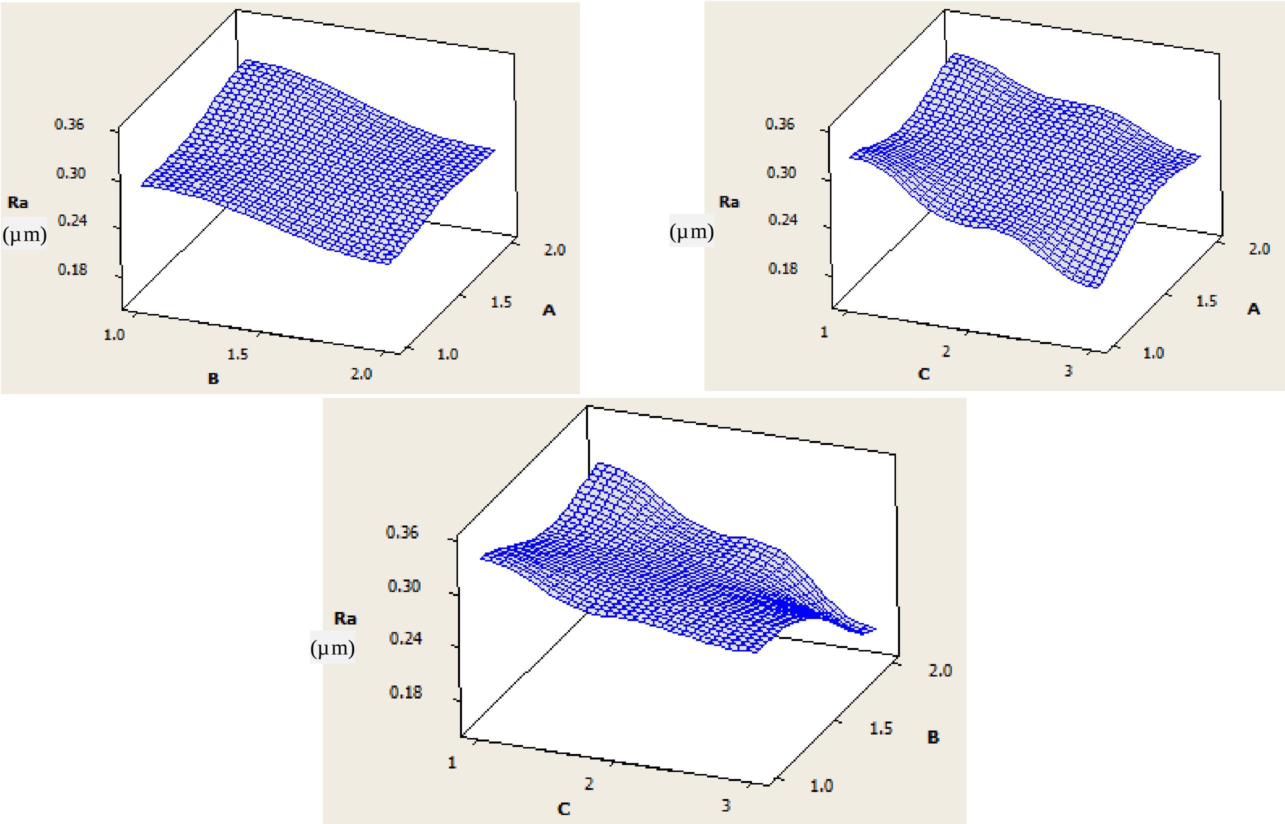

Figure4. 3D diagrams of surface roughness for different parameters including: the size of Al_2O_3 NPs (A), volume concentration of NPs in the base fluid (B), mixing ratio of Al_2O_3–MWCNT NPs (C)

As seen in Figure 4, the variation in the slope of the 3D surface diagram,which is an indication of the surface roughness variations, is higher when the mixing ratio of Al_2O_3–MWCNT NPs (parameter C) is involved in the diagrams. This shows that the effect of the mixing ratio of Al_2O_3–MWCNT NPson surface roughness variations is more than that of the other two parameters, namely the size of Al_2O_3 NPs (parameter A) and volume concentration of NPs in the base fluid (parameter B).

4. Conclusion

In this research, we studied the application of MQL with hybrid nano fluid in the grinding of Inconel 600 alloy. First, the input parameters of the grinding were determined. Then, the design of experiments using full factorial method was performed. Following that, the effect of three parameters including the size of Al_2O_3nanoparticles, the volume concentration of nanoparticles in the base fluid, and the mixing ratio of Al_2O_3–MWCNT nanoparticleson the surface quality was investigated. The findings of the study are summarized as follows:

1. The maximum surface roughness (R_a= 0.622µm) was obtained in dry grinding. Moreover, the minimum surface roughness (R_a= 0.15µm) was achieved in MQL grinding using nano fluid with size of Al_2O_3 NPs = 20nm, volume concentration= 0.6%, and mixing ratio of NPs= 75%-25%. The surface roughness value for MQL grinding with pure oil was also found to be less than that of wet grinding with Z1 fluid.

2. The results indicated that in MQL experiments where hybrid nano fluid with Al_2O_3- MWCNT NPs mixing ratio of 25%-75% was applied, the surface roughness was found to be higher compare to that of experiments using MQL-Pure oil. These results suggest that an excessive increase of the MWCNT weight percentage in the hybrid nano fluid would adversely affect the surface quality of the workpiece.
3. As the size of Al_2O_3nanoparticles increases in the hybrid nano fluid, the surface roughness increases. Using 20-nanometer Al_2O_3 nano particles in the hybrid nano fluid would cut less deeply than the 50-nanometer ones on the surface and therefore the surface roughness decreases. Although the particles mesh of the grinding wheel is an influential factor on the surface roughness, the mean value of surface roughness in grinding with hybrid nano fluids is less than that of both MQL grinding with pure oil and wet grinding. This indicates that when Al_2O_3 NPs in the nano fluid are placed in the contact zone between the grinding tool and the workpiece, they might diminish the effect of particles mesh of the grinding wheel and they even act as a dominating factor in removing the material from the workpiece surface during the grinding process.
4. When grinding with hybrid nano fluid, as the volume concentration of nano particles in the base fluid increases from 0.2% to 0.6%, the surface roughness decreases. The increase in the volume concentration results in an increased number of nano particles in the hybrid nano fluid, thereby causing a higher surface quality. A further increase in the volume concentration of nano particles more than 0.6% when the mixing ratio of Al_2O_3- MWCNT nano particles is maintained at 25%-75%would cause particles agglomeration in the hybrid nano fluid which leads to a lower nano fluid performance and as a result, a lower surface quality.
5. The experimental results confirm that the surface roughness decreases as the mixing ratio of Al_2O_3-MWCNT nano particles changes from 25%-75% to 75%-25%. The presence of MWCNT particles leads to an increased heat transmission from the grinding zone. MWCNT particles also move into the space between the Al_2O_3 nano particles and would prevent an excessive crushing of Al_2O_3 nano particles, and thereby improve the performance of Al_2O_3 nano particles. However, an excessive increase of MWCNTs volume concentration in the hybrid nano fluid would not help in surface roughness improvement. Therefore, Al_2O_3 abrasive nano particles are more effective than soft and flexible MWCNT nano particles in reducing the surface roughness because of Al_2O_3 nano particles ability to prevent the formation of the built up edge.

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