Investigating a novel Ag/ZnO based hybrid nanofluid for sustainable machining of Inconel 718 under nanofluid based minimum quantity lubrication

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Abstract

Sustainable machining, with implementation of eco-friendly dry and minimum quantity lubrication (MQL) methods, has gained attraction of researchers and engineers to solve the environmental and health allied issues caused by bulk usage of the conventional cutting fluids. Nanofluids have recently became more obvious choice as a cutting fluid in MQL applications owing to their superior thermo-physical properties. In this work, a novel hybrid nanofluid, consisting of Ag coated ZnO (Ag/ZnO) nanoparticles in ethylene glycol base, has been proposed as cutting fluid for MQL application. Initially, the Ag/ZnO hybrid nanoparticles were synthesized by a chemical precursor method. Then, synthesized nanoparticles were blended in ethylene glycol at several volume concentrations (Φ = 0.05% to 0.2%). The nanofluids were characterized for their thermo-physical properties and stability criterion, and then a nanofluid with the best performance was selected for nanofluid based MQL (NFMQL) experiments. The performance of NFMQL was compared with dry, MQL environments during milling of difficult-to-cut Inconel 718 superalloy with PVD coated carbide inserts. Taguchi L9 orthogonal array was incorporated for experimental design to investigate the effect of cutting speed, feed rate and machining environment on the machining performance in terms of the average surface roughness and cutting temperature. Analysis of variance shown that the cutting environment contributed to the average surface roughness and cutting temperature by 24.52 % and 44.74%, respectively. As compared to dry and MQL condition, the NFMQL improved the surface finish by 23.5 % and 13.07 %, respectively, and reduced the cutting temperature by 15.38 % and 8.56 %, respectively, owing to proposed hybrid nanofluids enhanced lubrication and heat dissipation properties. Furthermore, the field emission scanning electron microscopic (FESEM) images of used cutting tool inserts reveal that the NFMQL condition induces the minimum tool wear as compared with MQL and dry environments. Finally, the multi-response optimization was achieved through the implementation of Taguchi grey relational analysis (TGRA) with the optimum combination of cutting speed of 30 m/min, feed rate of 0.036 mm/tooth, and NFMQL cutting environment.

Keywords: Sustainable machining, MQL, NFMQL, Milling, Inconel 718, Hybrid nanofluid.

Nomenclature:

MQL: minimum quantity lubrication

NFMQL: nanofluid based minimum quantity lubrication

CNC: computer numerical control

CBN: cubic boron nitride

MRR: material removal rate

MWCNT: multi-walled carbon nanotube

SDS: sodium dodecyl sulfate

PVA: poly vinyl alcohol

FESEM: field emission scanning electron microscope

EDX: energy dispersive x-ray

BUE: built-up-edge

DOF: degree of freedom

R_a: average surface roughness

μ: viscosity

Φ: volume concentration

ρ: density

hn: hybrid nanofluid

bf: base fluid

ANOVA: Analysis of variance

S/N ratio: Signal-to-noise ratio

TGRA: Taguchi grey relational analysis

GRG: grey relational grade

1. Introduction

Conventional machining of difficult-to-cut Inconel 718 has always been challenging operation owing to severe cutting tool wear, deprived surface finish, problems in chip formation, and, more importantly, poor dissipation of excessive heat generated at cutting zone. Due to the promising properties viz. high-temperature strength, best corrosion and fatigue resistance, Inconel 718 superalloy finds numerous applications in atomic reactor, aviation parts, food processing and chemical equipment and heavy-duty marine machinery [1]. However, those superior properties also make Inconel 718 a difficult-to-cut material. To ease the machining, the practice of metal working fluids (MWF's) in flood lubrication mode is a typical strategy adopted in industries for dissipation of heat liberated in the machining of such difficult-to-cut materials. The flood lubrication generally improves the machining performance by dissipating the heat released at the cutting region and yields a better surface finish, tool life and chip removal [2]. However, the bulk uses of the MWF's in flood lubrication often account for 16-

20% of total machining costs, in addition to their handling and management costs. MWF's result in health hazards and leads to environmental pollution [2]. Furthermore, the MWF's tend to degrade with time due to bacterial growth and also requires treatment before dumping into the sewage system [3].

Global responsiveness towards sustainable manufacturing and customer's awareness about the environment friendly products has derived the attention of machining industries to abate or abolish the use of MWF's. In this regard, several alternatives like cryogenic lubrication, dry machining, minimum quantity lubrication (MQL) and solid lubricant assisted machining have been investigated and developed. Among these alternatives, researchers, of late, have focused their attention on MQL technique owing to its benefits such as improved machining performance, enhanced tool life, optimal use of MWF's, and effective heat dissipation from cutting zone [4].

The MQL uses a mist spray of cutting fluid, which is more efficient than flood cooling [5]. Gupta et al. [6] examined and optimized the MQL aided turning of Inconel 718 with CBN inserts. They observed that rise in the feed rate results in higher cutting forces while the material removal rate (MRR) increases at higher cutting speed. The performance of MQL aided milling of Inconel 718 has been compared with that of dry and flood assisted milling by Singh et al. [7]. They claimed that MQL results in better machining performance reducing the cutting tool flank wear related to flood and dry conditions. In other research, Ucun et al. [8] reported micro-machining of Inconel 718 with different coated cutting tools in MQL assisted and dry conditions. They claimed that coating materials have substantial influence on tool life and tool wear at MQL environment.

Biodegradability is critically essential considering human health and the environment. For meeting biodegradability, vegetable oils and easters, owing to their renewability, environment friendly nature and less toxicity, are obvious choices to prepare cutting fluids [9]. Therefore, use of vegetable oils as a MQL coolant has been also suggested in the literature [3, 10, 11]. Although, Obikawa et al. [12] reported that the MQL conditions are not always suitable for better machining performance, especially when enormous heat produced during machining of difficult-to-cut materials. Hence, an enhanced MQL fluid should be developed with higher lubrication and cooling capacities. Such enhancement for MQL is possible with use of nanofluids which have high thermal conductivity suitable for better heat dissipation during cutting operation. Nanofluids are synthesized by dispersion of nanoparticles (size less than 100nm) in the base fluids such as esters, vegetable oils, synthetic oils, etc. This process augments the thermo-physical properties of nanofluids suitable for effective heat transfer medium [13]. Yi et al. [14] proposed that practice of graphene oxide nanofluids results in reduced cutting temperatures and cutting forces at the cutting region during turning of Ti6Al4V. They also noted that graphene oxide nanofluids yield increased lubrication and reduced friction forces. Gaurav et al. [11] proposed suistanable machining of Ti6Al4V using jajoba vegetable oil with and without molybdenum disulfide nano-particles ($nMoS_2$) for pure MQL and NFMQL machining, respectively. They reported that addition of $nMoS_2$ based jajoba oil significantly enhaces the machining performance. Cui et al. [15] reported effects of the biomimetic microstructure, the multi-walled carbon nanotubes based vegetable-oil nanofluid MQL and their interaction attributes in minimizing the specific cutting energy and reduction of emission of harmful gases during the machining.

However, the limiting factor for the use of nanofluid as coolant in machining operations could be the improper stability in the base fluid [16]. Typically, various surfactants are mixed in base fluid for uniform dispersion of nanoparticles to improve the stability. However, the use of surfactants such as Tween20, Tween80 and sodium dodecyl sulfate (SDS) reduces the thermal conductivity of the coolants and, hence, they are not the best suitable option for coolants where cooling is a major job. Therefore, development of nanofluid with better a stability as well as enhanced thermo-physical properties is important consideration.

Another important aspect in machining is to optimize the process performance whilst lessening the negative effects on on health and environment. Thus, in this study, TGRA approach was employed to find the optimal machining conditions for the multiple quality characteristics. With application of TGRA, a mult-response optimization can be accomplished easily unlike the traditional mono-optimization. Deng's TGRA approach typically used to quantify the degree of approximation amid the sequences using the Grey Relational Grade. Lately, few academics have successfully shown the application of TGRA approach for the multi-response optimization improving the overall performance of the machining processes [17, 18]. Therefore, we employed TGRA for the multi-response optimization of face milling of Inconel 718 under different machining environments.

The literature review disclosed a need of synthesis of a nanofluid with better thermal conductivity whilst retaining stability. Therefore, a hybrid nanofluid comprising of the silver coated zinc oxide (Ag/ZnO) hybrid nanoparticles in ethylene glycol base has been proposed for NFMQL application in this study. Initially, Ag/ZnO nanoparticles were synthesized and characterized and then they were dispersed at different volume concentrations in base fluid. Further, the prepared nanofluids were characterized for their thermo-physical properties viz. zeta potential, effective thermal conductivity, and viscosity. Then, nanofluid with better properties was chosen for NFMQL application. The machining performance of Inconel 718 was investigated under different machining conditions in terms of average surface roughness, cutting temperature and tool wear. Finally, TGRA approach was implemented to find the best machining conditions considering the multiple quality characteristics.

2. Experimentation

2.1 Preparation and characterization of hybrid nanofluids

The hybrid nanofluids were blended by two-step approach. Initially, the Ag/ZnO nanoparticles were prepared by the chemical precursor process. The method for the synthesis of Ag/ZnO nanoparticles is schematically represented in Fig. 1. The sole-gel chemical reaction of the PVA, sucrose, zinc salt and Silver salt was carried out. A fine polymer-coated powder of zinc was acquired by stirring the aqueous phase of PVA and sucrose at 24 hr. For a proper reaction, the solution was heated to 65-75 ºC and, concurrently, the zinc salt was added (pH ~9) to upkeep hydrogenation of the Zn^+ ions. These fine polymers coated zinc salt powder was then mixed in the silver nitrate solution using magnetic stirring at 50-60 ºC. Lastly, the acquired powder was heated at 500-600 ºC for 2 hours to obtain the recrystallized ZnO nanoparticles covered with a steady thin shell coat of Ag. The primary purpose of this defined shape nanoparticles synthesis was to attain the Ag coated ZnO nanoparticle for taking benefit of both the characteristics of the nanoparticles and the achievement of the stable nanofluid suitable for use in the MQL process. Such synthesis can realise the nanoparticles up to size of 20 nm [19].

The surface morphology of the synthesized nanoparticles was confirmed by the FESEM (Carl Zeiss® SUPRA 55) images. The clusters of Ag/ZnO nanoparticles in flower petal structure can be observed in Fig. 2(a). These clusters are in the range of 500 nm - 1 µm containing 25-30 nanoparticles. A closer view of Ag/ZnO nanoparticles shown in Fig. 2(b) by a high-resolution tunneling electron microscope (TEM). This TEM image of the Ag/ZnO nanoparticle confirms the size of the nanoparticles in the order of 20-50 nm. The individual elemental constituent in the synthesized Ag/ZnO nanoparticle examined by energy dispersive x-ray (EDX) analysis. Fig. 2(c) verifies the occurrence of zinc, oxygen and silver in 34.81 %, 61.05 %, and 4.14 %, respectively. The synthesized hybrid nanoparticles had the Wurtzite crystal structure surrounded by flower petals with density of 6.24 gm/cm^3, and appeared in gray color. The detailed characterization representing the structural and electrical properties of the Ag/ZnO particles has been reported by our colleagues Jadhav and Biswas [19].

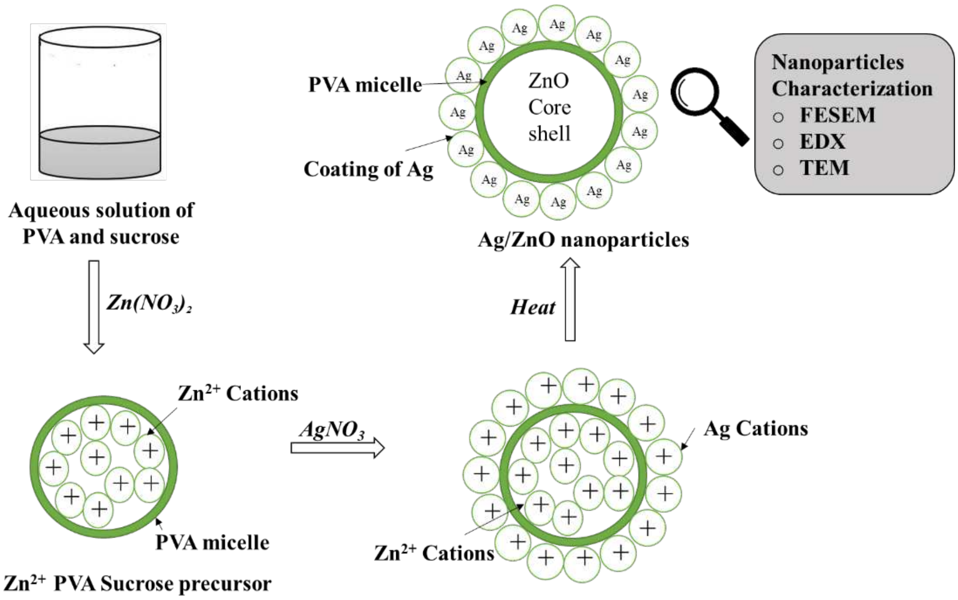


Fig. 1. Graphical representation of production of Ag/ZnO Hybrid nanoparticles.

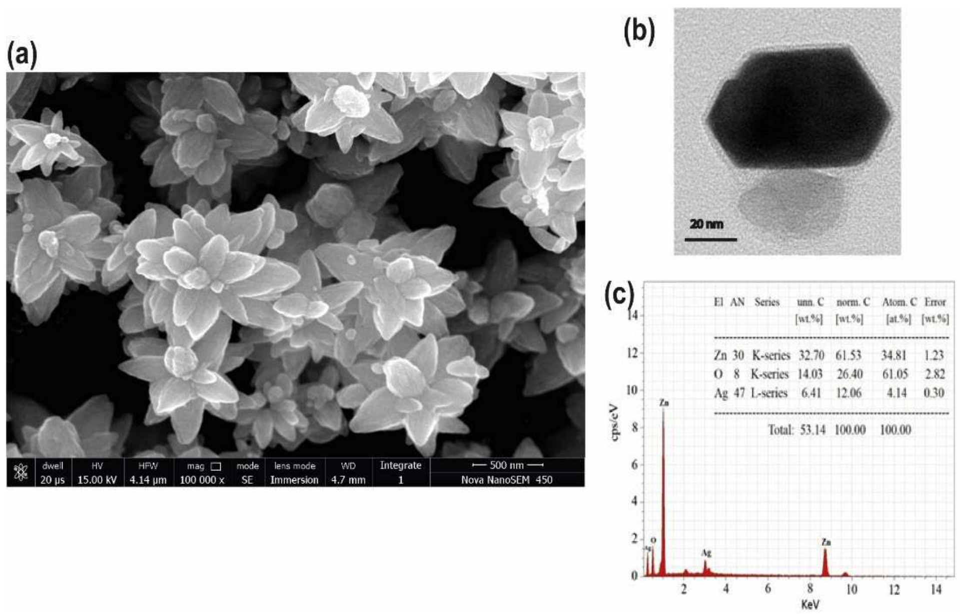


Fig. 2. Characterisation of Ag/ZnO nanoparticles, (a) FESEM image showing the hexagonal clusters Ag/ZnO nanoparticles, (b) TEM image, (c) EDX spectrum.

In the second step, these synthesized nanoparticles were dispersed in the ethylene glycol at volume concentration varied between 0.05 %, 0.10 %, 0.15 %, and 0.2 % (Eq. 1).

$$\Phi = \frac{\frac{m_{hn}}{\rho_{hn}}}{\frac{m_{bf}}{\rho_{bf}} + \frac{m_{hn}}{\rho_{hn}}} \tag{1}$$

The thermo-physical characteristics of ethylene glycol are depicted in Table 1.

Table 1 Properties of the ethylene glycol.

Property	**Value**
Flash point	111 °C
Viscosity	1.61×10^{-2} Pa·s
Density	1.11 gm/cm^3
Thermal conductivity	0.252 W/m^2-K

The stability is an important parameter to decide the nanofluids thermo-physical properties. To accomplish a stable dispersion of the nanoparticles, the prepared nanofluid was agitated by magnetic stirring and then ultrasonicated for 1 hour (see, Fig. 3). The nanofluid stability characterization was carried out by the two ways, namely, visual observation and by measuring the zeta potential values using (Malvern Instrument®, Nano-ZS).

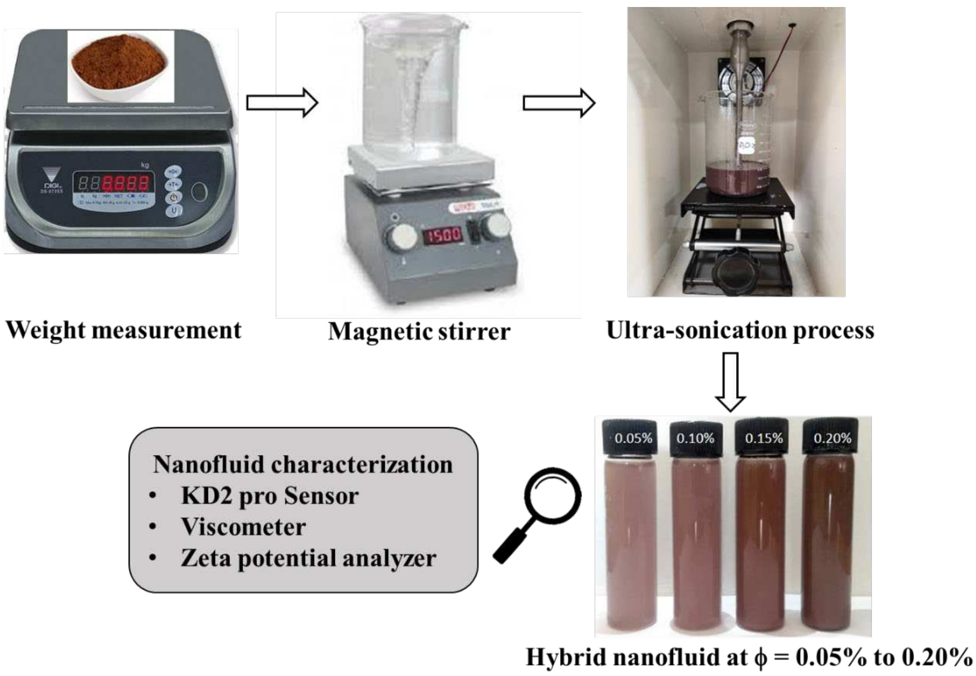


Fig. 3. Schematic procedure of synthesis of glycol-based Ag/ZnO hybrid nanofluid.

The prepared nanofluids at different concentrations of nanoparticles were examined for their thermo-physical properties viz. the thermal conductivity and dynamic viscosity at different temperatures. The thermal conductivity was measured by KD2 pro sensor because of its higher accuracy [20]. The viscosity of the prepared nanofluid was determined with the cone and plate viscometer.

2.2 Workpiece, tool and CNC milling with MQL setup

For the current research, commercially available Inconel 718 material was used and cut into plates of size 120 X10 X 6 mm. A 12 mm diameter indexable cutter (Secotools® R217.69-1212.0-06-2AN) purchased from Seco tools India Limited. The milling inserts (Secotools® XOMX060204R-M05 F40 M; clearance angle 15°, effective cutting edge length 5.5 mm, corner radius 0.40 mm, insert width 4.1 mm) used were coated grade carbide inserts with TiAlN coating obtained by the physical vapor deposition coating method. The TiAlN coating offers a better wear-resistant and reduced friction while machining difficult-to-cut materials. New inserts were used for each experimental run. Experimental runs were performed on the MTAB Maxmill+ vertical machining centre having X, Y and Z drives with limits as 480 mm, 360 mm and 500 mm, respectively, and with the accuracy of 0.01 mm. The Siemens 828D controller is equipped on the machine for programming and operations. An MQL setup was utilized which had external MQL nozzle to spray cutting fluid directly into the cutting region. The angle of jet with respect to tool axis was 45° and the distance between nozzle and tool face was kept 60 mm. This distance was selected such that the jet covers the entire face of cutting tool. The air pressure of 6 bar and flow rate of 35 ml/hr was selected for MQL spraying considered from the literature [7, 21].

2.3 Milling Experiments

The milling of Inconel 718 was performed varying three input machining parameters, namely, cutting speed, feed/tooth and cooling environment. The major goal of the work was to compare the effect of NFMQL environment with other cutting environments; therefore, cutting environment was selected as input parameter. Three cooling conditions were selected viz. dry, MQL and NFMQL. The dry condition involves milling without any coolant, while ethylene glycol was chosen as cutting fluid for MQL flow cooling conditions. For NFMQL, the nanofluid with the best properties was selected out of the prepared nanofluids. The three input parameters by considering three levels of each were chosen, as revealed in Table 2. Taguchi methodology is extensively used to design experiments, especially in the manufacturing domain. The orthogonal array-based designs provide an efficient approach to evaluate the effect of process factors on response variables and deliver optimum setting of factors impervious to noise. Taguchi L9 orthogonal array was chosen to accommodate these input factors and plan the experiments. The milling performance was analyzed in terms of average surface roughness and cutting temperature.

Table 2 Machining parameters and their levels.

Parameter	**Level 1**	**Level 2**	**Level 3**
Cutting speed (m/min)	30	45	60
Feed/tooth (mm/min)	0.036	0.046	0.056
Cooling environment	Dry	MQL	NFMQL

The average surface roughness (R_a) of the surface prior and after machining was analyzed using the surface roughness profilometer (Mitutoyo® SJ-210). The profilometer contained a diamond stylus connected to its probe which moves over the surface to trace the crest and troughs of the surface. The conformance standard of the profilometer was ISO-1997 with filter-gauss. The measurements were performed with a sampling length of 0.8 mm, an evaluation length of 4mm and travel length of 4.8 mm, and the running at a speed of 0.5 mm/min with diamond stylus. R_a measurements were performed at five locations on the workpiece and the mean value was considered for further analysis in this paper. The maximum cutting temperature was measured using an infrared camera (Optris® PI 400i) set to measure temperature range between 0 to 800°C. The insert wear was observed using images taken by FESEM. The schematic of experimental setup is presented in Fig. 4.

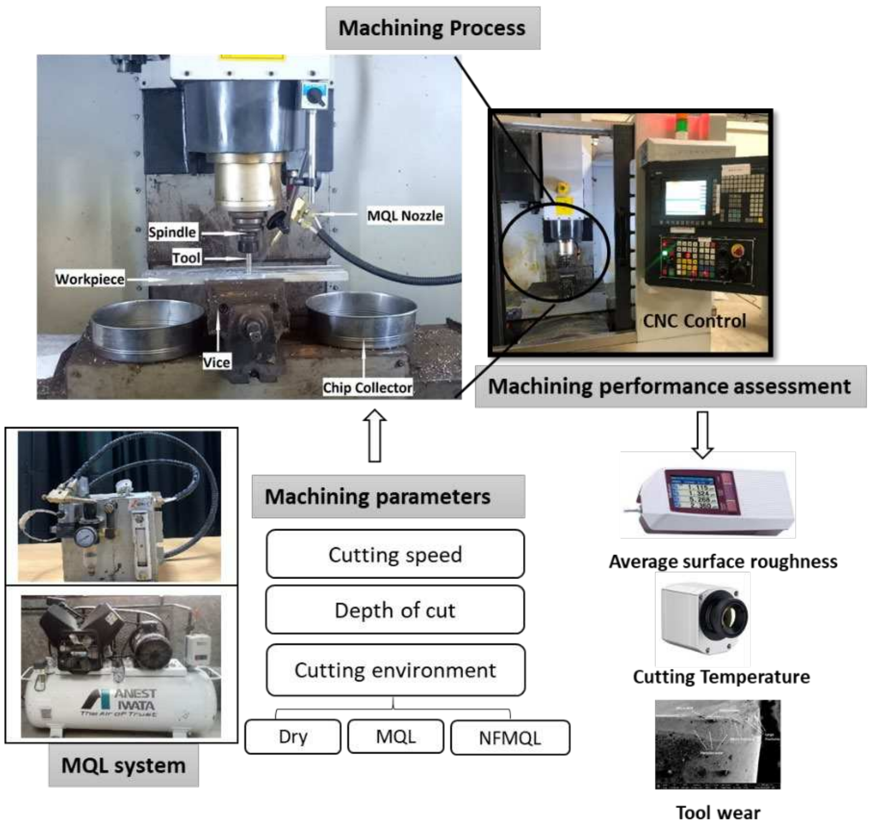


Fig. 4. Schematic of CNC milling experiments.

3. Results and discussion

3.1 Characterization and selection of nanofluids

As described previously, the nanofluids with numerous concentrations (viz. 0.05%, 0.10%, 0.15%, and 0.2%) by volume of hybrid nanoparticles were prepared and then their thermo-physical properties were characterized for selection of nanofluid with best properties for NFMQL based milling tests.

For the stability measurement, the visual tests were carried out by observing the prepared nanofluids for possible sedimentation/agglomeration of the nanoparticles. The sedimentation/agglomeration of nanoparticles at the bottom of flasks was not found until 15 days for all nanofluids (see Fig. 5). Therefore, the prepared nanofluids considered to be having good stability. The measurement of zeta potential values, referred to as the repulsive forces between particles is another essential aspect to highlight the stability of such nanofluids [22]. The stability of prepared nanofluids was analyzed in terms of zeta potential values and visual observations recorded at day 1 and day 15 (see, Fig. 5). According to the stabilization theory, the agglomeration of nanoparticles is inversely proportional to the electrostatic repulsion in particles and higher electrostatic repulsion typically observed for high zeta potential values. It is stated that nanofluids that have absolute zeta potential values between 30 to 60 mV are very stable. Fig. 5 (a) shows the zeta potential values for prepared nanofluids measured at room temperature (25 ºC). Although the zeta potential values declined with a rise in nanoparticle concentration, the zeta potential values were well in within the range of 30 to 60 mV (range for higher stability) Φ = 0.05 % to 0.2 %. But for the 0.25% volume concentration, the zeta potential value droped below 30 mV. Therefore, according to the zeta potential tests and visual observations (Fig. 7 (b)), the prepared nanofluids with a volume concentration between Φ = 0.05% to 0.2% were perceived to be stable and having good dispersion characteristics. Thus, the nanofluids with volume concentration 0.05% to 0.20% were selected for further characterization.

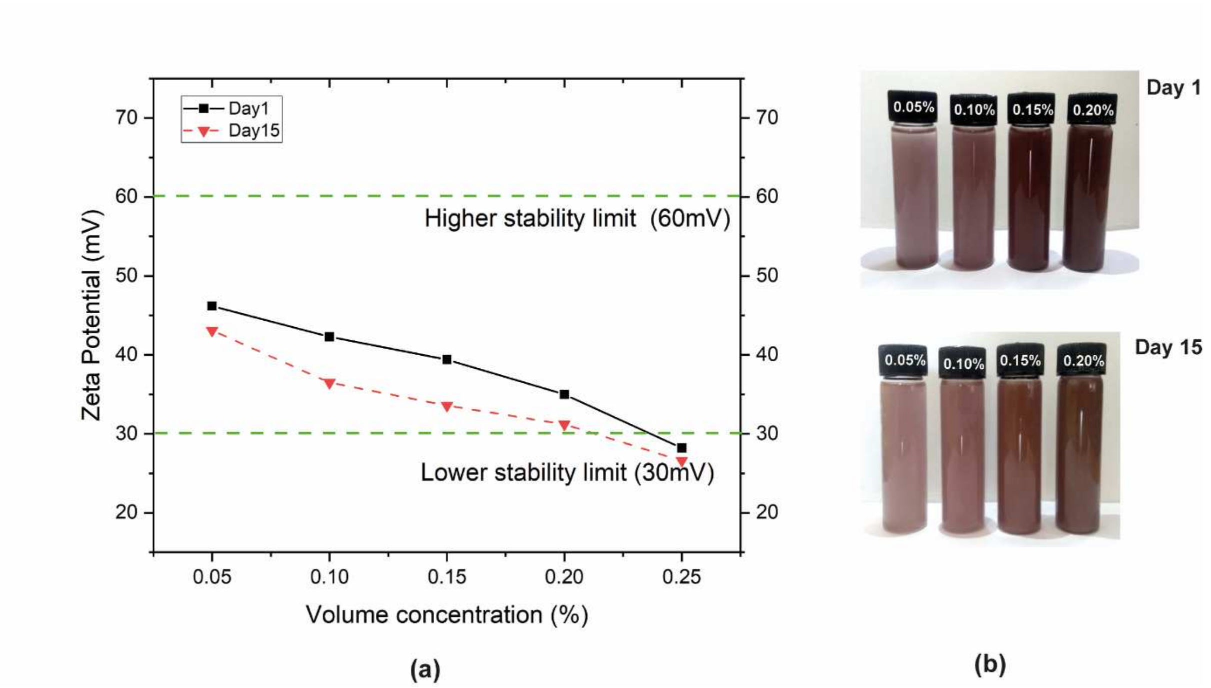
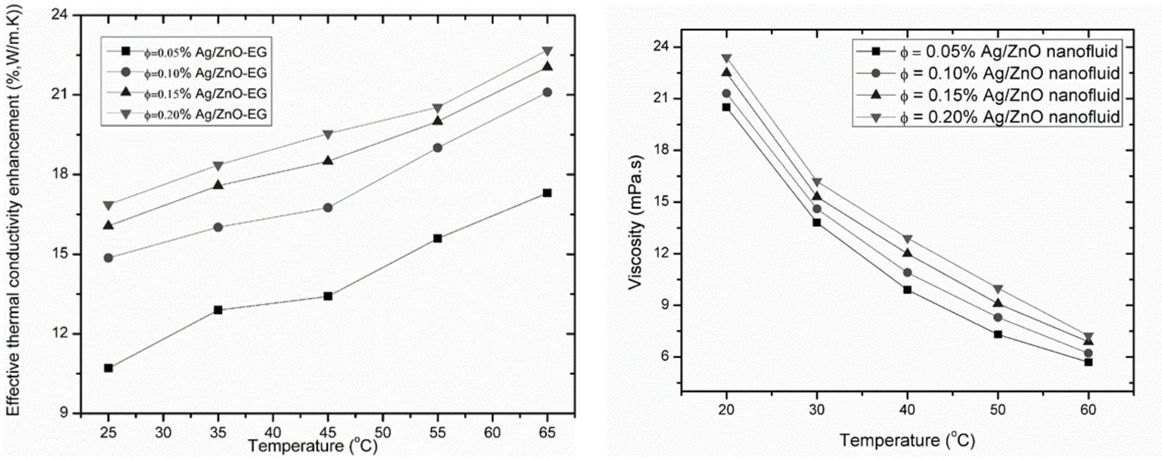


Fig. 5. Stability investigation of hybrid nanofluids at different concentrations (a) zeta potential, (b) photographs.

The thermal conductivity of synthesized nanofluids was analysed with KD2 sensor. The accuracy of ±2 % was quantified for the measurement of thermal conductivities of DI water and ethylene glycol. Then, the thermal conductivity of the prepared nanofluids was measured at varying temperature ranging from o 25 to 65 $^{\circ}$C (Fig. 9). An increased thermal conductivity was seen for increasing the values of the concentration of nanoparticles and temperature. It is found that for 0.20% volume concentration of nanoparticle, the maximum 15% enhancement in thermal conductivity comped with ethylene glycol at 25 $^{\circ}$C was recorded. High thermal conductivity yields improved Brownian motion of the nanoparticles that increases the lattice vibration between the molecules.

Similarly, the viscosity of fluids was appeared to be increasing with an increase in concentrations of nanoparticles. It is appreciated that viscosity value of nanofluid drops with a rise in temperature, but this decrement is marginal compared with viscosity of the glycol (see, Fig. 6). The fluid with higher viscosity and higher thermal conductivity generally well suited as coolant in machining operations. Therefore, the hybrid nanofluid with 0.2% concentration of Ag/ZnO was selected as a coolant for NFMQL operation in further study.



(a) (b)

Fig. 6. Properties of hybrid nanofluid at different temperature, (a) effective thermal conductivity, (b) dynamic viscosity of the hybrid nanofluid at different temperature.

3.2 Effect of process parameters on responses

As discussed previously, the milling experiments were planned via Taguchi L9 orthogonal array. Table 3 displays the experimental runs and measured response values and S/N ratio values for response variables. To assess the effect of input machining parameters on response variables, lower-the-better S/N ratio criteria was used. The lower values of R_a and cutting temperature demonstrates the better machining performance. Therefore, lower-the-better criteria was used to calculate the S/N ratios. Higher the S/N ratio typically correspond to optimum value of input factor to yield better process performance. The S/N ratio values for both responses were determined using following equation.

$$\frac{S}{N}(\eta) = -10\ log\left[\frac{1}{9}\sum_{i=1}^{9} y_i^2\right] \qquad (2)$$

Where, y_i is the measured value of response for ith run.

In the following sections, the effects of input factors on response variables have been discussed.

Table 3 Effect of machining factors on the responses.

Run	Input machining parameters			Response variables			
	Cutting speed (m/min)	Feed rate (mm/tooth)	Cutting environment	Average surface roughness (µm)		Cutting temperature (°C)	
				Mean R_a Value	S/N ratio (dB)	Value	S/N ratio (dB)
1	30	0.036	Dry	2.26	-7.082	238	-47.531
2	30	0.046	MQL	2.37	-7.495	245	-47.783
3	30	0.056	NFMQL	2.15	-6.649	223	-46.966
4	45	0.036	MQL	1.68	-4.506	248	-47.889
5	45	0.046	NFMQL	1.61	-4.136	238	-47.531
6	45	0.056	DRY	2.35	-7.421	290	-49.248
7	60	0.036	NFMQL	1.11	-0.906	244	-47.748
8	60	0.046	DRY	1.75	-4.861	305	-49.686
9	60	0.056	MQL	1.55	-3.807	278	-48.881

3.2.1 Average surface roughness (R_a)

The impact of cutting speed, feed/tooth and cooling environment on the average surface roughness values is depicted in Fig. 7. It is clear that the dry machining associated with the poorest surface finish, while MQL and NFMQL reduced the R_a value significantly. In absence of the cooling and lubrication, tool undergoes the adhesion wear resulting in the high temperature and stresses at tool tip [23]. The lowest R_a was witnessed at NFMQL having 20 % hybrid Ag/ZnO nanoparticles. The introduction of cooling and lubrication is known for enhancing the surface finish while machining operations [17]. Although, usage of nanofluid in

MQL yielded better surface finish that MQL owing to its better thermo-physical properties. It was found the NFMQL improves the surface finish by 23.5 % and 13.07 % as related to dry and MQL cooling environments, respectively. The NFMQL attributes the adequate lubrication and heat withdrawal from machining zone, thus, leading positive impact on surface finish. The nanoparticles could avoid the welding of chips on inserts and owing to ball bearing effect of nanoparticles, the chips slide easily over the tool surface. Generally, the surface roughness depends on feed rate and nose radius, and with a rise in feed/tooth the R_a rises as seen from Fig. 7. The mean value of surface roughness at 0.036 mm/min of feed/tooth is 1.683 µm which increased by 13.5 % to 1.91 µm and by 19.84 % to 2.017 µm at feed/tooth of 0.046 and 0.056, respectively. At high cutting speed, the R_a values were observed to be reducing. Such trend of decrease of surface roughness with an increase in cutting speed can be explained by considering role of vibration at low cutting speed. At low cutting speed, machine may experience vibration, especially while cutting difficult-to-cut superalloys and hard materials, since workpiece material in not adequately warm to result the material softening. Higher cutting speeds result in high cutting temperature which allows easy deformation of the workpiece without being torn, thus improving the surface finish [24]. Contrarily, the higher cutting speed decreases the vibration and chatter effects, and as a result, the R_a decreases. Further, with an increase in cutting speed, the required cutting force for cutting action decreases. Similar, trend of decrease of R_a with an increase in cutting speed value up to 60 m/min was also reported by Mia et al. [25]. They reported that when the cutting speed rises further above 60 mm/min, it result in increased R_a values due to larger stickiness (i.e. adhesion) of workpiece and formation of built-up-edge (BUE).

The S/N ratio trend for different input factors settings can be seen from Fig. 7. According to S/N ratio analysis, the higher S/N ratio is desirable for optimum setting of input parameters. The optimum machining performance to yield lower the surface roughness can be realised at cutting speed of 60 m/min (level 3), feed rate of 0.036 mm/tooth (level 1), and with NFMQL cutting environment (level 3). In other words, the higher cutting speed, lower feed rate and NFMQL cooling environment are ideal for achieving the better surface finish while milling of Inconel 718.

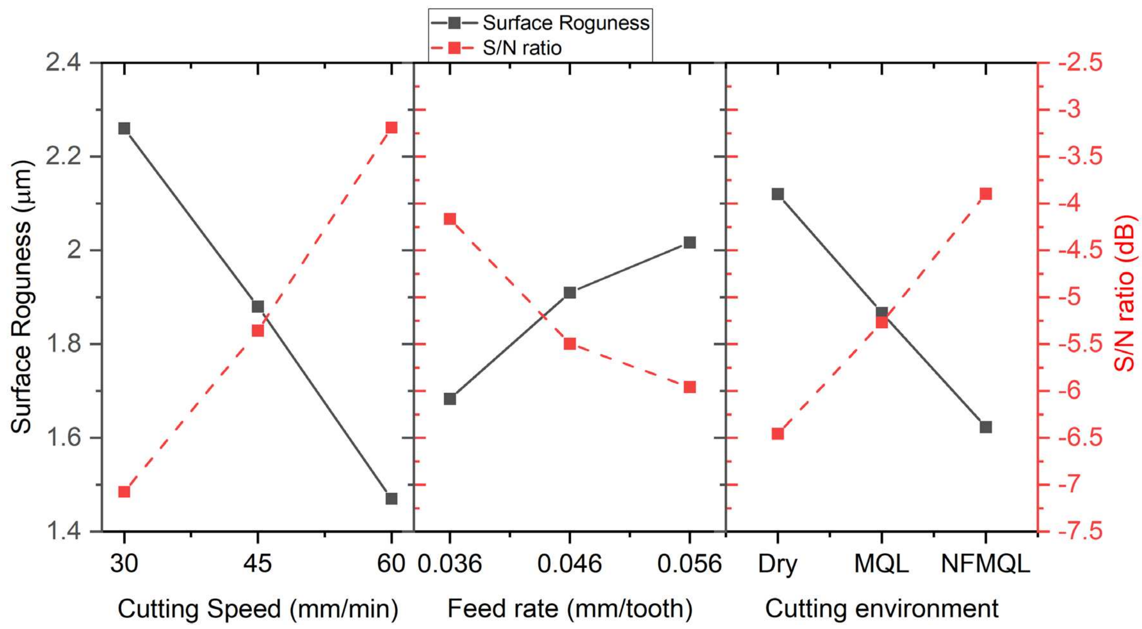


Fig. 7. Effect of machining factors on the surface roughness.

3.2.2 Cutting temperature

The cutting temperature often considered as a major factor in the machining process as it influence the tool wear, dimensional accuracy surface integrity, etc. The influence of cutting speed, feed/tooth and cutting environment on cutting temperature is shown in Fig. 8. Higher cutting speed and feed rate are known for increasing the cutting temperature (see, Fig. 8). Higher the cutting speed, higher is the kinetic energy. Such large kinetic energy results in the tremendous heat generation in cutting region owing to plastic deformation at primary deformation region and friction at tool-chip zone and tool-work zone [25]. Although high cutting speed generally results in increased cutting temperatures, it is pre-requisite for increased productivity to ensure cleaner productions. Thus, the use of cutting fluids becomes a prime requirement for lowering the cutting temperature and increasing productivity. Similarly, with an increase in feed/tooth value, cutting temperature seen to be increasing. It can be realized from Fig. 8 that the highest heat liberated at dry cutting environment while machining Inconel 718. Whereas, the lowest temperature, i.e. better heat dissipation, resulted in NFMQL cooling condition as compared to MQL condition. During dry machining, in the absence of cooling medium, heat dissipation is very poor and therefore, high temperatures can be observed in the cutting zone. The introduction of coolant fluid using MQL and NFMQL has a noteworthy effect on reducing the cutting temperature. The mist and air in MQL take out the convective heat transfer, while, the heat absorbed by ethylene glycol, which used as base fluid in MQL, results in both convective and evaporative heat transfer. The NFMQL cutting environment reduced the cutting temperature by 15.38 % and 8.56 % as compared to dry and MQL condition, respectively. The nanofluid with 0.2 % hybrid Ag/ZnO nanoparticles had significant enhancement in thermal conductivity owing to the high heat absorption ability of Ag/ZnO nanoparticles. Moreover, as described previously, nanoparticles improve the lubrication and helps in chips removal due to ball bearing effect. Thus, at NFMQL cooling, the heat dissipation in even faster and reduces the cutting zone temperature. Similar results regarding reduced cutting temperature with use of nanofluids during various machining operations are reported in [26, 27]. Su et al. [27] reported that the graphite-LB2000 NFMQL had a better performance than that of MQL and dry conditions and reduced the cutting temperature significantly. The lowest cutting temperature was observed while using hBN nanoparticles based NFMQL as compared to that of MQL and dry conditions by Yıldırım et al. [26]. They reported the reduction of the cutting temperature by 30% compared to dry machining.

The optimum parametric settings suggested by S/N ratio analysis for lowest cutting temperature are cutting speed of 30 m/min (level 1), feed rate of 0.036 mm/tooth (level 1), and NFMQL cutting environment (level 3). Hence, to achive a lower cutting temperature, low cutting speed, low feed rate and NFMQL environment settings found to be best input conditions.

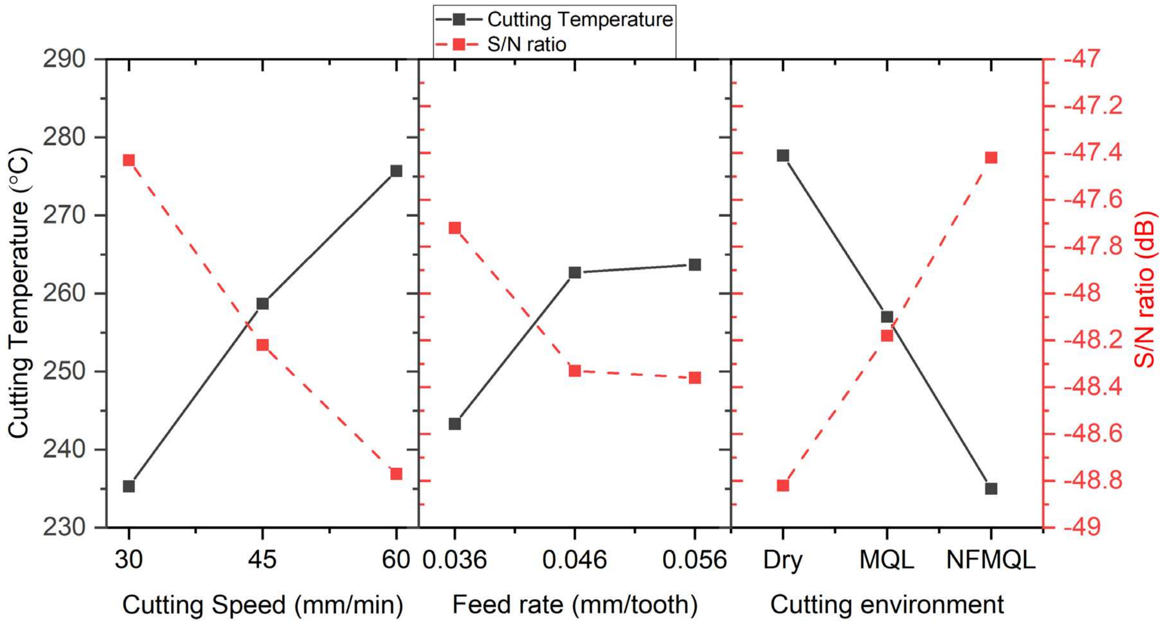


Fig. 8. Mean effect plot for cutting temperature.

3.2.3 Analysis of variance (ANOVA)

The statistical performance of the factors was assessed using the ANOVA at 95% confidence level and outcomes are depicted in Table 4. F values of the control factors indicated the significance of control factors with ANOVA analysis. P values less than 0.05 indicates whether the input factor has significant contribution on the response or not. As expected for milling operation, the cutting speed witnessed to be most significant factor for R_a contributing by 62.06 %. The feed rate and cutting environments contributes on R_a by 11.52 % and 24.52 %, respectively. The cutting temperature was affected by the cutting speed and feed/tooth by 40.30 % and 12.91 %, respectively. Both the cutting speed as well as the cutting environment found be having signifant effect on response variable since their corresponding P values are less that 0.05.

Table 4 ANOVA for surface roughness and cutting temperature

Factors	Degree of freedom	Sum of squares	Mean of squares	F	P	Percentage contribution %
<u>Surface roughness</u>						
Cutting Speed	2	0.9366	0.46830	32.90	0.029	62.06%
Feed Rate	2	0.1738	0.08693	6.11	0.141	11.52%
Cutting Environment	2	0.3701	0.18503	13.00	0.071	24.52%
Error	2	0.02847	0.01423			
Total	8	1.50907				
<u>Cutting temperature</u>						
Cutting Speed	2	2460.2	1230.11	19.81	0.048	40.30%
Feed Rate	2	788.2	394.11	6.35	0.136	12.91%
Cutting Environment	2	2731.6	1365.78	21.99	0.043	44.74%
Error	2	124.2	62.11			
Total	8	6104.2				

3.3 Effect of cutting environment on the tool wear

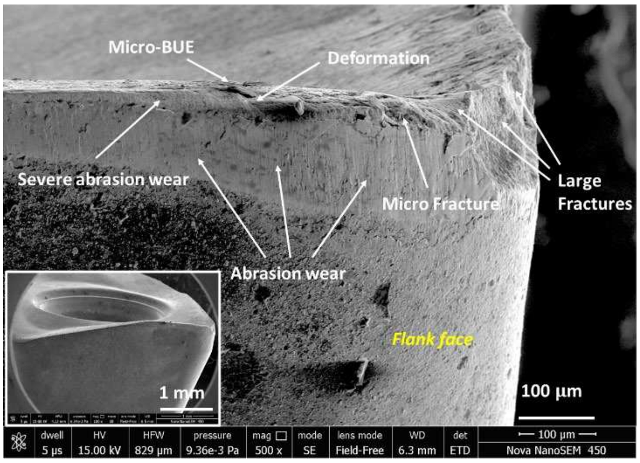
To investigate the influence of cooling/lubrication environment on tool wear, three additional experiments were conducted while milling difficult-to-cut Inconel 718 workpiece at dry, MQL and NFMQL conditions at a constant cutting speed of 60 m/min and feet/tooth of 0.06 mm/min. The microscopic images of inserts after dry, MQL and NFMQL milling captured using a scanning electron microscope are shown in Fig. 9 (a), (b), and (c), respectively.

A worse tool wear was witnessed for dry machining environment. The insert used in dry machining undergone deformation, microfractures, abrasive wear, and micro built-up-edge

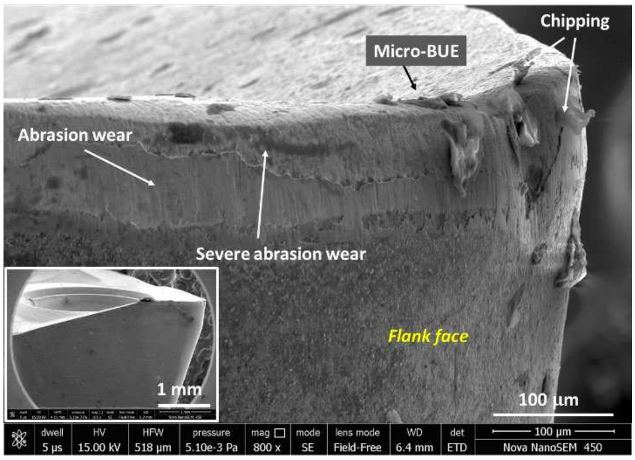
(BUE) formation. Similar observations were also reported in [28, 29]. Inconel 718 is hard and sticky superalloy and, often, its machining results in work hardening resulting in excessive stresses on cutting edges. At high cutting speed and feed values under dry environment, specific cutting energy and high friction leads to enormous heat liberation and, thus, cutting insert undergoes high tool wear. Under the application of MQL, NFMQL cooling environment, the insert wear was found to significantly less than that of dry conditions as seen from Fig. 9. In MQL, a little quantity of base oil is sprayed in the mist form, into the cutting region with the using compressed air, forming a thin oil film at tool-workpiece and tool-chip zone and reduces friction preventing the accumulation of heat. Moreover, the lubricating substance in MQL allows to pass away the heat produced due to friction at cutting tool. This decreases the tool wear also increases the tool life.

The MQL method is eco-friendly and safe for users if used with appropriate coolant which is desired in this study. The chips from MQL are non-corroded and recycled. Among the MQL and NFMQL, the least amount of wear was observed in NFMQL as demonstrated in Fig. 9 (b) and (c). Hybrid nanofluid consisting of Ag/ZnO nanoparticles shows a better effect due to its ability of high heat extraction from the cutting region. Similar observation regarding ability of nanofluid for enhanced heat extraction has been reported by Yıldırım et al. [26]. The best surface finish witnessed in NFMQL condition while the poor surface quality was observed in dry machining.

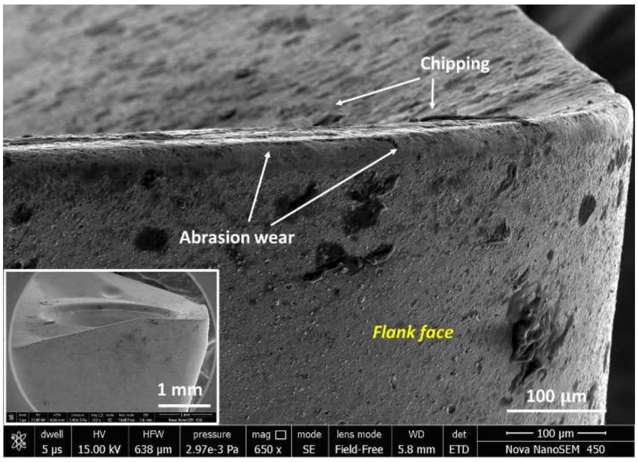
These preliminary experimental results show that the proposed hybrid Ag/ZnO nanofluid is superior for NFMQL application during milling of Inconel 718. However, an extensive experimental work is required to be done to critically examine the performance of proposed nanofluid at different concentration and cutting conditions. Further, study of the physics of droplet interaction, the surface chemical characterization after machining, etc. is required to to explain the action mechanism illustrating benefits of proposed hybrid nanofluid.



(a) dry



(b) MQL



(c) NFMQL

Fig. 9. FESEM images for tool wear at different cutting environment (a) Dry, (b) MQL, (c) NFMQL; (at cutting speed of 60 m/min and feed/tooth of 0.06 mm/min).

3.4 Taguchi grey relational analysis based multi-response optimization

In previous sections, the signal-to-noise (S/N) ratio analysis was used to determine the optimum sets of factors in single objective optimization for minimizing the average surface roughness and cutting temperature, separately. However, such approach is not suitable for multi-response optimization cases such as in the current work. Therefore, TGRA was applied for simultaneous optimization of the average surface roughness and cutting temperature. Initially, the grey relational generating based on “smaller the better” criteria was employed to normalise the measured response values since smaller surface roughness and cutting temperature are desirable characteristics [30]. The grey relational generating on "smaller the better" was accomplished through following equation:

$$x_{ij} = \frac{max_j y_{ij} - y_{ij}}{max_j y_{ij} - min_j y_{ij}} \qquad (3)$$

Where, y_{ij} for the ith experimental result in the jth experiment.

Generally, the greater normalized values signify an enhanced performance, and the best normalized value should be unity. Subsequently, the grey relation coefficients were determined to describe the correlation between the best and the normalized response values. The grey relation coefficient was calculated using following equation,

$$\xi_{ij} = \frac{min_i min_j \left|x_i^0 - x_{ij}\right| + \zeta max_i max_j \left|x_i^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \zeta max_i max_j \left|x_i^0 - x_{ij}\right|} \qquad (4)$$

where x_i^0 is the best normalized value for the i^{th} response variable and ζ is the distinctive constant (here, assumed to be 0.5) which is defined in the range $0 \leq \zeta \leq 1$.

Finally, the grey relation grade (GRG) was determined by taking an average of the grey relation coefficient for respective response variable. The GRG value was determined using equation (5).

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m} \xi_{ij} \qquad (5)$$

where γ_j is the GRG of the j^{th} trial and 'm' is the number of response variables (here, m=2). Table 5 lists the calculated values of normalised input factors, grey relational coefficients and the GRG. The GRG values have been ordered from high to small value to decide their rank. The last column of Table 5 represents the calculated GRG values and the order in which it was ranked from high value to small. A higher value of the GRG exhibits the better performance of outputs for all results simultaneously. The experimental run 6 is marked as 1 and the combination of input factors for this run is the best possible combination of factors among the all runs. Therefore, the cutting speed of 30 mm/min, feed rate of 0.036 mm/tooth, and NFMQL cutting environment is the best combination showing the optimum parameters for multi-response optimization in the current experimental design. Since, a higher value of the GRG exhibits the better machining performance, therefore, the larger-the-better S/N ratio was used to find the optimal expertimental run for the multi-response optimization. Larger-the-better criteria for higher GRG is defined as follows:

$$\frac{S}{N}(\eta) = -10\ log_{10}\left[\frac{1}{9}\sum_{i=1}^{9}\frac{1}{y_i^2}\right] \qquad (6)$$

Where, y_i is the GRG value of response for ith run. In order to determine the effect of each level, the mean value of GRG and S/N ratios for GRG were calculated for the multiple quality characteristics are plotted in Fig. 10. The highest level of each factor directs the optimum level for that factor. In addition, the parameter with the highest difference between the maximum value and minimum value is the most contributing factor on gray relation grade. As seen from Fig. 10, the highest S/N ratio of GRG corresponds to optimum levels of machining factors are obtained as cutting speed at level 1 (30 mm/min), feed rate at level 1 (0.036 mm/tooth), and cutting environment at level 3 (NFMQL). The highest difference between the maximum value and minimum value of GRG was recorded for the cutting environment, the cutting environment is the as the most dominant factor following by feed rate and then cutting speed for multi-response characteristics.

Table 5 TGRA based grey relational generation, grey relational coefficient and grey relational grade.

Expt. No.	**Normalised values of response variables**		**Grey relational coefficient**		**Grey relational grade**	
	Surface roughness	**Cutting Temperature**	**Surface roughness**	**Cutting Temperature**	**Value**	**Rank**

1	0.08730	0.817073	0.35393	0.73214	0.54304	5
2	0.00000	0.731707	0.33333	0.65079	0.49206	7
3	0.17460	1.00000	0.37725	1.00000	0.68862	2
4	0.54762	0.695122	0.52500	0.62121	0.57311	4
5	0.60317	0.817073	0.55752	0.73214	0.64483	3
6	0.01587	0.182927	0.33690	0.37963	0.35826	9
7	1.00000	0.743902	1.00000	0.66129	0.83065	1
8	0.49206	0.00000	0.49606	0.33333	0.41470	8
9	0.65079	0.329268	0.58879	0.42708	0.50793	6

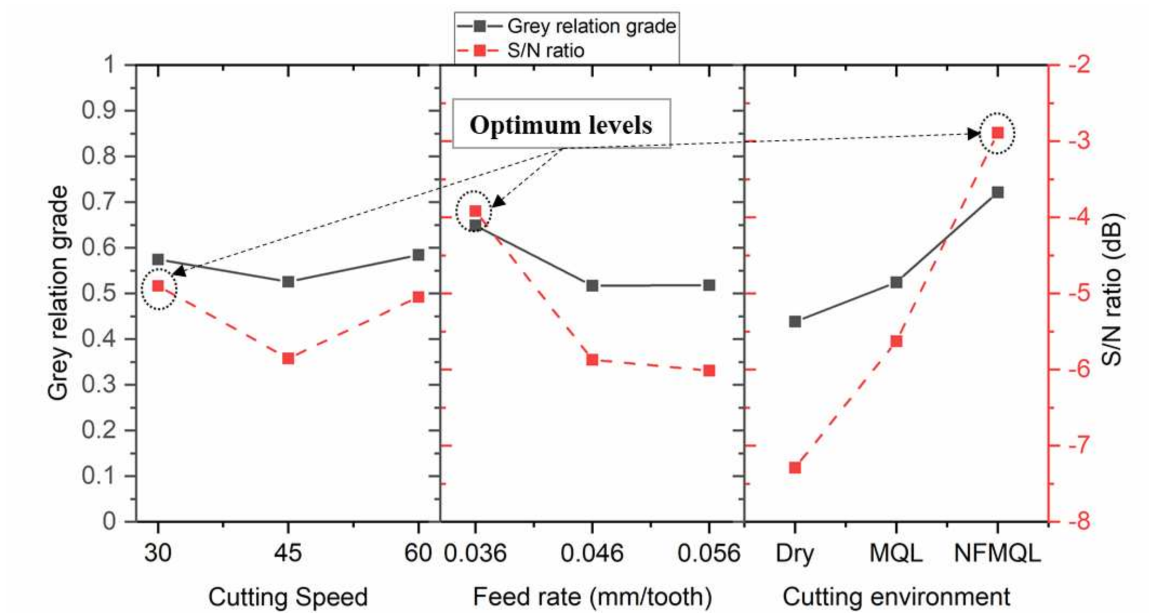


Fig. 10. Effect of machining input factors on the grey relation grade.

3.4.1 ANOVA analysis of GRG

ANOVA was applied to check the effect of input factors on the multi-response variables. The outcomes of ANOVA listed in Table 6 directed that the cutting speed, feed rate, and cutting environment significantly contributes (P <0.05) deciding the GRG values by 3.60 %, 20.67 %

and 75.67 %, respectively. Interestingly, the cutting environment found to be the most substantial parameter governing the multiple performance characteristics and contributes by 75.67 %, suggesting a positive impact on multiresponse machining characteristics. Thus, it can be claimed that NFMQL assisted milling in appropriate to improve the surface finish whilst reducing the cutting temperature. The proposed hybrid nanofluid found suitable for cleaner production in the machining domain.

Table 6 ANOVA for GRG.

Factors	**Degree of freedom**	**Sum of squares**	**Mean of squares**	**F**	**P**	**Percentage contribution %**
Cutting Speed	2	0.005999	0.003000	87.63	0.011	3.60%
Feed Rate	2	0.034425	0.017213	502.86	0.002	20.67%
Cutting Environment	2	0.126073	0.063036	1841.59	0.001	75.67%
Error	2	0.000068	0.000034			
Total	8	0.166566				

3.4.2 Confirmation experiments

Finally, the confirmation experiments were performed at optimal level of input factors to confirm the improvement in the responses variables. The estimated GRG at optimal set of input factors can be computed by following equation [30]:

$$\widehat{\propto} = \propto_m + \sum_{i=1}^{q} \overline{\propto}_i - \propto_m \quad \ldots (7)$$

here $\propto_m$ = is the total mean of the GRG, $\overline{\propto}_i$ is the mean of the GRG at the optimal level, and q is the number of the input factors that significantly affects the multiple response variables.

Table 7 shows a good agreement between the estimated GRG and experimental GRG obtained at optimum levels of input factors. Further, a percentage improvement of 25.04 % in GRG from initial factor setting (V_c-2 F_r-2, CE-3) to optimum factors setting (V_c-1 F_r-1, CE-3) was observed. Therefore, the current optimization results are claimed to be satisfactory and thus, improving the milling performance of Inconel 718.

Table 7 Results of machining performance using initial and optimal machining parameter.

Machining Parameters	Initial machining parameters	Optimum machining parameters	
		Predicted	Experimental
	V_c-2 F_r-2, CE-3	V_c-1 F_r-1, CE-3	V_c-1 F_r-1, CE-3
Average surface roughness	1.61		1.80
Cutting temperature	238		202
Grey relation grade	0.6483	0.7971	0.81061

Improvement in grey relational grade = (0.81061 - 0.6483) = 0.16231 i.e., 25.04 %

4. Conclusions

In this study, a novel Ag/ZnO hybrid nanofluid was proposed for NFMQL application. Initially, hybrid Ag coated ZnO nanoparticles were synthesized and characterized. Four nanofluids with a different volume concentration of these nanoparticles were prepared and characterized for their thermo-physical properties. Finally, the nanofluid with best characteristics was implemented for NFMQL application and its performance while machining Inconel 718 was compared with MQL and dry environments. The following conclusions were drawn from this study.

- The Ag coated ZnO hybrid nanoparticles were successfully synthesized by the chemical precursor process. The hybrid nanofluids comprising of several volume concentrations (Φ = 0.05 to 0.20%) of Ag/ZnO nanoparticles were characterized for their thermo-physical properties. The nanofluid with 0.20 % concentration of Ag/ZnO particles was found best suitable for NFMQL application.

- The high cutting speed and feed/tooth yielded in a better surface finish, while the lowest cutting temperature was attained at the low cutting speed and feed/tooth values under the NFMQL environment.
- The NFMQL environment also induced a reduced amount of tool wear indorsed by hybrid nanofluid in improving the sliding mechanism, abridged friction at tool-work and chip-tool interfaces. Thus, the NFMQL can be claimed to be a better choice for sustainable production with enhanced product quality.
- The cutting environment was found to significantly contributing by 75.67 % to grey relational grade based on the multi-response characteristics (i.e. for decreasing the cutting temperature whilst enhancing the surface quality). The multi-response optimized machining performance was realised at the cutting speed (level 1): 30 m/min, feed rate (level 1): 0.036 mm/tooth, and NFMQL cutting environment (level 3).

In the future work, the effect of different nanofluid concentration, MQL air-pressure and flow rate on material removal rate, surface roughness, cutting temperature and tool wear characteristics (considering the mechanism tool-work interface) are required to be investigated to further validate the performance of proposed nanofluid in this study.

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