Int J Adv Manuf Technol (2012) 60:149–160
DOI 10.1007/s00170-011-3599-5

ORIGINAL ARTICLE

AFM investigation in grinding process with nanofluids using Taguchi analysis

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Received: 29 January 2011 / Accepted: 16 August 2011 / Published online: 2 September 2011

Abstract Nanofluids for grinding process are prepared by mixing the multiwall carbon nanotubes with SAE20W40 oil. In this experimental study, the surface roughness and micro cracks are analysed. The material AISI D3 tool steel is most frequently use for mould and dies which is preferred to analyse the surface characteristics. Experimental results indicate that the surface finish of the machined work piece increases from micro level to nano level. L8 orthogonal array was used to optimize the machining parameters in Taguchi design of experiment technique using Minitab 15 software. Empirical model for the prediction of output parameters has been developed using regression analysis and the results are compared empirically for with and without nanofluids in grinding process. The analysis of variance and *F* test were used to determine the significant parameter affecting the surface roughness. Atomic force microscopy analysis indicated that carbon nanotube mixed with nanofluid in grinding process has improved the surface characteristics like surface roughness and micro cracks.

Keywords Multiwall carbon nanotube · Grinding · Roughness · Regression · ANOVA · Nanofluids · Atomic force microscope

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1 Introduction

The behaviour of fluids at micro level is different from macro fluid in that surface tension, energy dissipation and fluidic resistance start to dominate the system. Molecular transport between them must often be through diffusion. Nanofluids are having low Reynolds number. When Reynolds number is low, the viscous interaction between wall and fluid is strong and there is no turbulence or vortices. Transport by diffusion can be very effective means of mixing in the low Reynolds number regime. Conventionally fluids have poor thermal conductivity compare to solids. Conventional fluids contain mm or μm size particles do not work with miniaturized technology because they can clog the tiny channels of these devices. Nanofluids are new class of advanced heat transfer fluids engineered by dispersing nanoparticles smaller than 100 nm in diameter in conventional heat transfer fluids.

There are major challenges in the rapid settling of these particles in fluids. The nanoparticles that suspended much longer than micro particles remain indefinite. Surface area to volume ratio is much larger in million times than micro particles. These property enhanced flow, heat transfer and other characteristics. Nanoparticles of graphite, carbon nanotube (CNT), Al_2O_3, CuO, SiC and PCM materials are mixed with base fluids of water, engine oil, glycol and other lubricants, bio fluids and polymer solutions. Here 10 g of multiwall carbon nanotube is mixed with 1 l of SAE20W40 oil to enhanced thermal conductivity and critical heat transfer applications. Thermal conductivity (T_c) increased at low nanoparticle concentration. The highest thermal conductivity enhancement ever achieved in nanoliquids is shown in Fig. 1. One hundred fifty percent increased in conductivity of oil ~1 vol.%. Critical heat flux increased significantly.

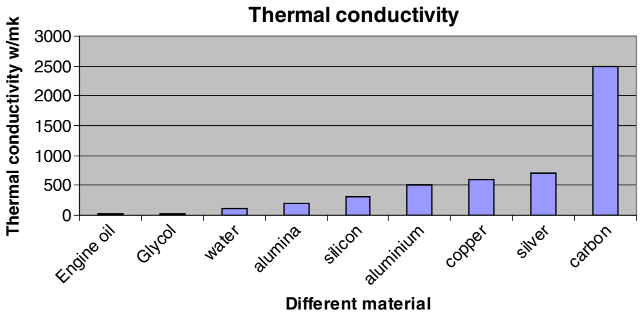

Fig. 1 Thermal conductivity of different materials

CNTs have been of great interest, both from a fundamental point of view and for future application. The most eye catching features of these structures are their mechanical, optical and chemical characteristics, which open a way to the machining application. CNTs have a tremendously high surface area, good electrical conductivity and very importantly, their linear geometry makes their surface highly accessible to the electrolyte. This CNT is 100 times stronger than steel and weight is 1/6th weight of steel. CNT having high strength to weight ratio is used in aero space industry. Young's modulus of CNTs is over 1 TPa, 70 GPa for aluminium and steel of 210 and 700 GPa for C-fibre. The strength to weight ratio is 500 times greater than aluminium. Maximum strain will be 10% much higher than any material. The thermal properties of nanotubes are also very impressive.

Nanotubes are stable in vacuum up to 2,800°C and in air up to 750°C. The heat transmission is predicted to be as high as 6,000 W/mK at room temperature. This can be compared with nearly pure diamond, which is a very good heat conductor and transmits 3,320 W/mK. The density of bundled nanotubes is 1.33–1.40 g/cm^3. This is very low, as compared with aluminium, possessing a density of 2.7 g/cm^3. CNTs having very high current carrying capacity, excellent field emitter and high aspect ratio. There is a considerable change in the mixture of abrasive particles with Carbon nanotube when compared to the normal one. These results indicate that CNTs can be used as an additive in the lubricant. The flash point is increased when carbon nanotube is mixed with cutting fluid uniformly, so the cutting fluid can withstand more heat which is generated during grinding process. Also due to heat and friction the white layer formation can be controlled by using carbon nanotubes.

1.1 Literature review

Mamalis et al. [1] written to give a consolidated view of the synthesis, the properties and applications of carbon nanotubes, with the aim of drawing attention to useful available information and to enhancing interest in this new highly advanced technological field for the researcher and the manufacturing engineer. Xie et al. [2] developed the thermal conductivity of the fluid and surface finishing of the test surface can be largely enhanced by the suspended nanoparticles. Choi [3] suggest that the smaller the particles, the greater the quantum effects, which means greater changes to the bulk physical properties of the nano-composite, and this phenomenon is widely accepted as not being properly understood. Nanofluids are simply standard fluids such as water, engine oil, ethylene glycol and toluene, but including a small volume percentage, usually less than 5% of evenly dispersed nanoparticles, which are usually metallic. Bin Shen [4] gives a detailed view about the synthesis, physical and thermal properties and the amount of nanoparticles to be used for the purpose of machining using nano lubricants. You et al. [5] proposed to use nano structures directly to fully utilize the nice mechanical and thermal properties for nano machining. CNTs were directly used as cutting grains. For the CNT grains, epoxy was used as one of the bonding materials and a series of CNT grinding wheels were fabricated to demonstrate the effectiveness of the proposed new type of abrasive tool. The CNT wheels are made of 1% MWCNTs or multiwall CNTs. Preliminary test results show that CNT wheels without functionalization or chemical treatment give the best average results. Carbon nanotubes can be used as cutting grains for nano machining. Zhang et al. [6] proposed a theoretical study of the CNT uncut chip model that was conducted together with preliminary experimental tests to investigate the chip generation in the nano machining process. A grain spacing model and a feed of work piece per cutting edge model were developed. Chip gelling effect was found. The reasons were due to agglomeration and epoxy melting. Syam Sundar et al. [7] suggested an excellent overview of the important physical phenomena necessary for the determination of effective thermal conductivity of nano-fluid. The heat transfer fluids with suspended ultra fine particles of nanometre size are named as nanofluids, which have opened a new dimension in heat transfer processes. This work presents the increase of thermal conductivity with temperatures for nanofluids with water as base fluid and particles of Al_2O_3 or CuO as suspension material. Prabhu et al. [8] analysed the surface characteristics of tool steel material using multiwall carbon nanotube to improve the surface finish of material to nano level. Carbon nanotube mixed nanofluids are special interests to researchers because of the novel properties of carbon nanotubes—extraordinary strength, unique electrical properties and efficient conductors of heat. CNTs are fullerene-related structures that consist of either a grapheme cylinder or a number of concentric cylinders [9]. Choi et al.

[10] measured the effective thermal conductivity of SWCNTs dispersed in synthetic (poly-α-olefin) oil and reported the enhancement up to a 150% in conductivity at approximately 1 vol.% CNT, which is by far the highest thermal conductivity enhancement ever achieved in a liquid [11]. Guu [12] proposed that the surface morphology, surface roughness and micro crack of AISI D2 tool steel machined by the electrical discharge machining (EDM) process were analysed by means of the atomic force microscopy (AFM) technique. Chiang et al. [13] proposed the methodology for modelling and analysis of the rapidly resolidified layer of spheroidal graphite cast iron in the EDM process using the response surface methodology. The results of analysis of variance (ANOVA) indicate that the proposed mathematical model obtained can adequately describes the performance within the limits of the factors being studied.

Narender Singh et al. [14] proposed the multi-response optimization of the process parameters viz. metal removal rate (MRR), tool wear rate, taper, radial overcut and surface roughness (SR) on electric discharge machining (EDM) of Al–10%SiCP as cast metal matrix composites using orthogonal array with Grey relational analysis is reported.

Lin et al. [15] developed the force assisted standard EDM machine. The effects of magnetic force on EDM machining characteristics were explored. Moreover, this work adopted an L18 orthogonal array based on Taguchi method to conduct a series of experiments, and statistically evaluated the experimental data by ANOVA. Chattopadhyay et al. [16] investigate the machining characteristics of EN-8 steel with copper as a tool electrode during rotary electrical discharge machining process. The empirical models for prediction of output parameters have been developed using linear regression analysis by applying logarithmic data transformation of non-linear equation. Three independent input parameters of the model viz. peak current, pulse on time and rotational speed of tool electrode are chosen as variables for evaluating the output parameters such as MRR, electrode wear ratio (EWR) and SR. Analysis of the results, by using Taguchi's recommended signal–noise ratio formulae and ANOVA, has been conducted to identify the significant parameters and their degree of contribution in the process output. The analysed results show that peak current and pulse on time are the most significant and significant parameters for MRR and EWR, respectively.

AISI D3 tool steel is one of the carbon steels alloyed with Mo, Cr and V and is widely used for various dies and cutters for its high strength and wear resistance due to formation of chrome carbider in heat treatment. Table 1 lists the chemical composition (wt.%) of the material and the hardness of AISI D3 tool steel 256 HV was tested in Mettex lab, Chennai according to OES-CML/WP/35 and IS 1586-2000 standards (Table 1).

Multi-walled nanotubes consist of multiple rolled layers (concentric tubes) of graphite. Carbon nanotubes are a new form of carbon with unique electrical and mechanical properties. They can be considered as the result of folding graphite layers into carbon cylinders and may be composed of a several shells. The unique properties of multiwall nanotubes are proving to be a rich source of new physics and could also lead to new applications in materials and devices. The sources of carbon nanotubes are received from Cheap tubes Inc., USA (http://www.cheaptubes.com; Table 2, Fig. 2).

1.2 Research methodology

The specimen was made of the AISI D3 tool steel, which is widely used in the mould industry. The raw materials were machined using tungsten carbide cutting tool. The specimens were made to a size of diameter 20 mm and length 100 mm. The raw material was heated to 1,030°C at a heating rate of 200°C/min in muffle furnace. It was kept at 1,030°C for 1 h and then quenched. After quenching, the specimens were tempered at 520°C for 2 h and then air cooled. The hardness obtained for the specimen is 256 VHC. The machining was carried out by surface grinding machine with average grain size of 10 μm vitrified alumina grinding wheel. For all samples, the nanofluids were prepared by dispersing 10 g of MWCNTs into the SAE20W40 oil base fluid (500 ml). The mixture was then ultrasonicated for 10 min at 100% amplitude using a 130 W, 20 kHz ultrasonic processor (Nanotechnology research centre, SRM University, Chennai) and it was followed by 20 min stirring using a magnetic stirrer. The process was repeated until the total mixing time was 1 h. The prepared samples were set at rest for 24 h before conducting any viscosity and thermal conductivity measurements. The experiments were carried out by using L8 orthogonal array of Taguchi design of experiments. The regression analyses are used to predict the error between actual measurements with regression model values. The AFM surface characteristics of AISI D3 tool steel was analysed using carbon nanotube mixed nanofluids.

Table 1 Chemical composition of the AISI D3 tool steel [wt. %]

Elements	C	Si	Mn	Mo	Cr	S	V	P	Fe
Wt.%	2.108	0.434	0.446	0.042	11.819	0.02	0.054	0.024	Balance

Table 2 Specification of MWCNTs

Outer diameter	10 to 20 nm
Length	10 to 30 μm
Purity	>95 wt.%
Ash	<1.5 wt.%
Specific surface area	>233 m^2/g
Electrical conductivity	>10^{-2} S/cm

2 Result and discussions

The properties of nanofluids (Table 3) are tested in Mettex lab, Chennai, India. Here considerable increase in the Flash and Fire point. It indicates that the heat harvesting capability of nano lubricant is increased. In real machining process, these characteristics of nanofluids playing a vital role in transferring heat during machining and also enhance the surface finish characteristics of the grinding process.

Viscosity is a measure of the internal resistance to motion of a fluid and is mainly due to the forces of cohesion between the fluid molecules. Viscosity is one of the most important properties of lubricating oil.

The formula used to finding the viscosity is

$$\rho_{\mathrm{t}} = \rho_{\mathrm{r}}(1 - 0.000657(T - T_{\mathrm{r}})) \quad (1)$$

$$V = ct - B/t \quad (2)$$

$$m = V \times Pt \quad (3)$$

ρ_{t} the density of oil at temperature T in °C [g/cm^3]
ρ_{r} the density of oil at room temperature [g/cm^3]
T the temperature of the oil [°C]
T_{r} the room temperature [°C]
t means Saybolt Seconds
V the absolute kinematic viscosity, [N s/m^2]
m the absolute dynamic viscosity, [Centipoise]

Where c and B are redwood constants given in Table 4.

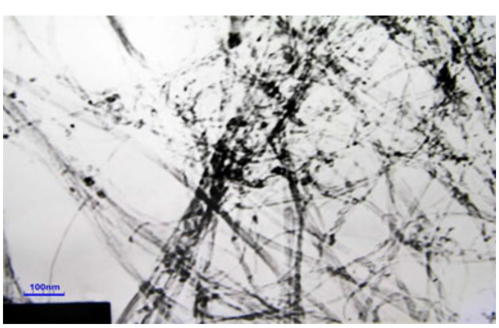

Fig. 2 TEM image of MWNTs 95 wt.% <8 nm OD

Table 3 Properties of nanofluids

Thermal property	Without nanofluids	With nanofluids
Flash point (°C)	200	210
Fire point (°C)	235	250

Graph is drawn between the kinematic viscosity and temperature for normal lubricant and nano lubricant. Kinematic viscosity and dynamic viscosity of lubricant with and without nanoparticle is shown in Fig. 3.

An increase in the viscosity of the nano lubricant is observed from the graphical results due to which the pressure forces perpendicular to the surface of the material were reduced to a greater extent and thus the surface compositional characteristics does not change much. It also saves the deformation of the grain boundary. Particularly from graphical results, it is observed that the high temperature region the viscosity difference is more for nano lubricant.

2.1 Design of experiments

Taguchi design of experiments technique permits us to carry out the modelling and analysis of the influence of process variables (design factors) on the response variables. In the present study, the depth of cut (d, mm), spindle speed (N, rpm) and feed rate (f, mm/min) have been selected as design factors while other parameters have been assumed to be constant over the experimental domain. The process variables (design factors) with their values on different levels are listed in Table 5. The selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as the recommended specifications for different work piece and tool material combinations. Two levels within the operating range of the parameters have been selected for each of the factors. In the present investigation, L8 orthogonal array design has been considered for experimentation. The interaction effect of process parameters has been assumed negligible. The experimental values along with design matrix are shown in Table 6.

To determine the effect of the nanofluids on grinding machining process on the surface roughness of the AISI D3 tool steel, the surface profiles of the grinding specimens

Table 4 Redwood constant

Time taken	c	B
70–855	0.264	190
855–2050	0.247	85

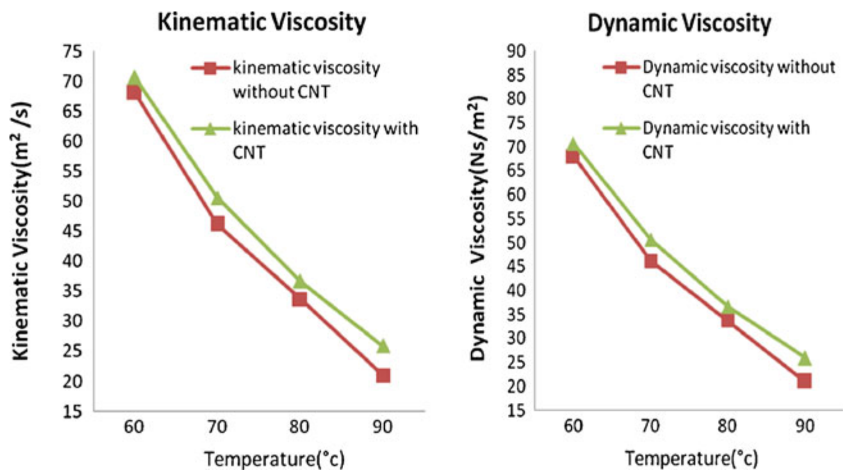

Fig. 3 Kinematic and dynamic viscosity of without and with nanofluid

were measured by surface roughness tester (Hommel Tester T500). The measured roughness parameters along with design matrix have been shown in Table 6. It clearly shows an increase in the surface finish of the materials due to addition of the Carbon nanotube in SAE 20W40 oil lubricant. This is due to the fact that the CNT added to the material actually occupies the nanovoids generated during the machining of the material and give a good surface finish.

S/N ratio calculated based on quality of the characteristics. The objective function of this method is to improve the surface finish of grinding machining process using nanofluids of SAE 20W40 oil with MWCNT. So the smaller the best *S/N* ratio is calculated. The formula used for calculating the *S/N* ratio is given below:

Smaller the best

$$\frac{S}{N}\text{Ratio}(\eta) = -10\log 10\frac{1}{n}\sum_{i=1}^{n} y^2 \qquad (4)$$

n=number of experiments and y=number of response value

From Fig. 4 the factor effect diagram for surface roughness without using nanofluids denoted that the speed, feed and depth of cut are analysed and optimized in level 1, level 2 and level 2 for improving surface roughness. The based on experiments, the optimum level setting of parameters are A1B2C2 for without nanofluids and A1B1C2 for with nanofluids.

Table 5 Identifying control factors and their levels

Parameters	Control factor	Units	Level 1	Level 2
A	Speed (*N*)	rpm	2,000	2,500
B	Feed (*f*)	mm/min	1.9	2.5
C	Depth of cut (*d*)	mm	0.1	0.2

The predicted *S/N* ratio $\acute{\eta}$ using the optimal levels of the machining parameters can be calculated as:

$$\eta' = \eta_m + \sum\nolimits_{i=1}^{p} \eta_i - \eta_m \qquad (5)$$

η_m—total mean of *S/N* ratio, η_i—mean of *S/N* ratio at the optimum level and p is the number of main machining parameters that significantly affect the performance.

Predicted surface roughness without nanofluids Ra (y)= 0.21 μm
Actual surface roughness without nanofluids Ra (y)= 0.29 μm
Predicted surface roughness with nanofluids Ra (y)= 0.344 μm
Actual surface roughness with nanofluids Ra (y)= 0.19 μm

The confirmation experiment is the final step in the first iteration of the design of experiment process. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiments were conducted by setting the process parameters at optimum level. The cutting speed of 2,000 rpm, feed of 2.5 mm/s and depth of cut of 0.2 mm as optimum parameters and the actual surface roughness of 0.29 μm was obtained without nanofluids compared with predicted surface roughness of 0.21 μm. Similar way with nanofluids, the confirmation test is carried out with a cutting speed of 2,000 rpm, feed of 1.9 mm/s and depth of cut 0.2 mm as optimum parameters and the actual surface roughness was obtained with nanofluids of 0.19 μm compared with predicted surface roughness of 0.344 μm.

Table 6 Experimental results along with design matrix

Experiment no.	Coded values			Surface roughness without nanofluids (Ra)	Surface roughness with nanofluids (Ra)	*S*/*N* ratio without nanofluid (η)	*S*/*N* ratio with nanofluid (η)
	Speed	Feed	Depth of cut				
1	1	1	1	0.38	0.26	8.404328	11.7005
2	1	1	2	0.39	0.25	8.178708	14.4249
3	1	2	1	0.37	0.26	8.635966	14.8945
4	1	2	2	0.29	0.27	10.75204	12.7654
5	2	1	1	0.57	0.33	4.882503	10.7520
6	2	1	2	0.56	0.36	5.036239	11.7005
7	2	2	1	0.51	0.40	5.848596	7.9588
8	2	2	2	0.40	0.34	7.9588	9.8970
				Mean(μ)		7.462148	11.76173

2.2 The relationship between surface roughness (Ra) and machining parameter (*S*, *F*, *D*) with and without using nanofluids

Empirical expressions have been developed to evaluate the relationship between input and output parameters. The average output values of surface roughness have been used to construct the empirical expressions. The empirical model was developed based on relationship between surface roughness with cutting speed, feed and depth of cut in grinding process.

The empirical model was based on [16]

$$Y = A(X1)^{a}(X2)^{b}(X3)^{c} \tag{6}$$

Y surface roughness (μm)
A coefficient
*X*1 speed (rpm)
*X*2 feed (mm/rev)
*X*3 depth of cut (mm)

The above non-linear equation is converted to linear form by logarithmic transformation and can be written as

$$\mathrm{Log}(Y) = \mathrm{Log}A + a\,\mathrm{Log}(X1) + b\,\mathrm{Log}(X2) + c\,\mathrm{Log}(X3) \tag{7}$$

Now the above Eq. 6 can be written as

$$\widehat{\mathrm{Y}} = \beta 0 + \beta 1 \times x1 + \beta 2 \times x2 + \beta 3 \times x3 \tag{8}$$

where $\widehat{\mathrm{Y}}$ is the true value of dependent machining output on a logarithmic scale, $x1$, $x2$ and $x3$ are the logarithmic transformation of the different input parameters. $\beta 0$, $\beta 1$, $\beta 2$ and $\beta 3$ are corresponding parameters to be estimated. Minitab 15 software has been used to estimate the parameters of the above first order model using the data shown in Table 6.

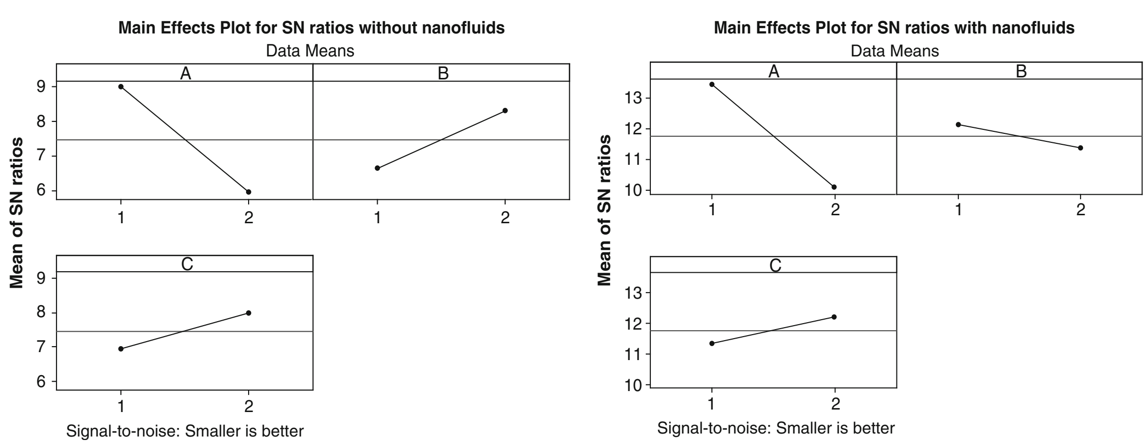

Fig. 4 Factor effect diagram for without (*left*) and with (*right*) nanofluids in grinding process

Table 7 Comparison of regression model with experiment measurements for with and without using nanofluids

Experiment no.	Without nanofluids surface roughness (μm)			With nanofluids surface roughness (μm)		
	Experimental measurements	Regression model	Predicted error (%)	Experimental measurements	Regression model	Predicted error (%)
1	0.38	0.4213	−10.86	0.26	0.24473	5.87
2	0.39	0.3738	4.15	0.25	0.24148	3.60
3	0.37	0.3385	8.51	0.26	0.27725	−6.53
4	0.29	0.291	−0.34	0.27	0.274	−1.48
5	0.57	0.5738	−0.67	0.33	0.34723	−5.10
6	0.56	0.5263	6.01	0.36	0.34398	5.55
7	0.51	0.491	3.72	0.4	0.37975	5.00
8	0.4	0.4435	−10.87	0.34	0.3765	−10.58

The developed empirical model [16] for surface roughness without nanofluids is

$$\mathrm{Ra} = A\ (S)^a (F)^b (D)^c \qquad (9)$$

a, *b* and *c* are coefficients determined by regression analysis.

Where

A 0.121
a 0.000305
b −0.138
c −0.475

The regression analysis of the experimental data yields the semi empirical model

$$\text{Ra without nanofluids (Ra)} = 0.121(S)^{0.000305}(F)^{-0.138}(D)^{-0.475} \qquad (10)$$

The developed empirical model for surface roughness with nanofluids is

$$\mathrm{Ra} = A(S)^a(F)^b(D)^c \qquad (11)$$

here

A −0.265
a 0.000205
b 0.0542
c −0.325

The regression analysis of the experimental data yields the semi empirical model

$$\text{Ra with nanofluids (Ra)} = 0.265(S)^{0.000205}(F)^{0.0542}(D)^{-0.325} \qquad (12)$$

The results of regression analysis are compared with experiments in Table 6 for eight check sets. The comparison results are depicted in Table 7. This method is suitable for estimating surface roughness in an acceptable error ranges. The model generation of regression model took just a couple of seconds. From the results, the error of measurements that occurs in surface roughness with nanofluid is less than without nanofluids used as cutting fluid.

The results and exact validation are presented in Table 7, which shows that the maximum predicted is 8.51% for without CNT nanofluids and 5.87% for with CNT-based nanofluid. The empirical equations developed by first order model represented a good fit between experimental error and predicted values. The calculated error percentage

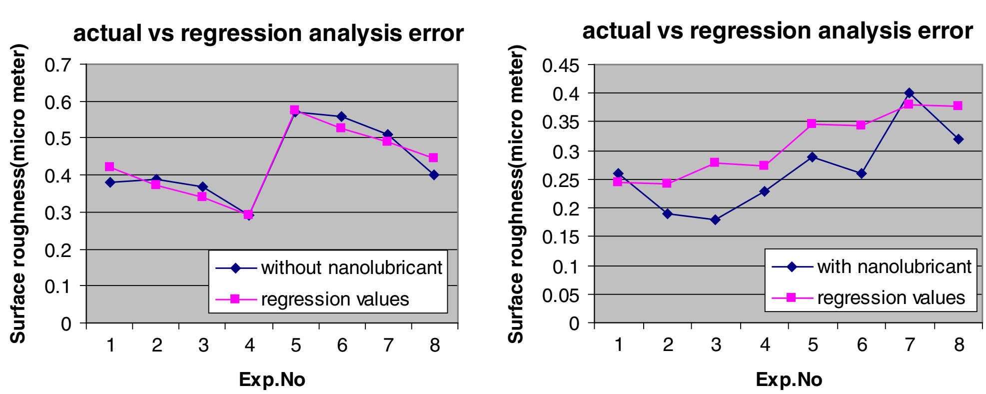

Fig. 5 Actual and regression analysis error for without (*left*) and with (*right*) using CNT nanofluids

Table 8 Results of ANOVA for the surface roughness with nanofluids

Machining parameters	Degree of freedom (f)	Sum of squares (SS_A)	Variance (V_A)	FA_o	P	Contribution (%)
Speed	1	0.046512	0.046512	19.90	0.011[a]	65.10
Feed	1	0.013612	0.013612	5.82	0.073	19.1
Depth of cut	1	0.001512	0.001512	0.65	0.466	2.1
Error	4	0.009350	0.002337			13.7
Total	7	0.070987				100

S=0.0483477, R^2 =86.83%, R^2 (adj)=76.95%

[a] Significant

between predicted and measured output values at each experimental condition is calculated as follows:

$$\text{Error}(\%) = ((\text{Experimental value} - \text{Predicted value})/\text{Experimental vlaue}) \times 100 \quad (13)$$

The range of maximum deviation in predicted error for surface roughness for without nanofluid is from −10.86% to 8.51% and with nanofluid is −10.58% to 5.87% shown in Fig. 5. Therefore, the developed simplified 1st order empirical models with main independent parameters have better fit enough.

2.3 ANOVA analysis

The purpose of analysis of variance is to find the significant factors affecting the machining process to improve the surface characteristics of AISI D3 tool steel material in grinding process. ANOVA gives clearly how the process parameters affect the response and the level of significance of the factor considered. The ANOVA table for surface roughness of with and without nanofluids is calculated.

The main output from an ANOVA study is arranged in Tables 8 and 9. In the ANOVA Table 8 for surface roughness with nanofluids, speed, feed and depth of cut are significant at a 95% confidence level. Therefore, effects of the control parameters are statistically significant at 95% confidence level. The value of R squared (R^2) for surface roughness is 0.8683, which signifies that the model can reasonably explain 86.83% of the variability in surface roughness. The adjusted R squared (R^2 adj) for the model is 0.7695, which is very close to the value of ordinary R^2, i.e. 0.8683. Thus, it can be stated that no non-significant terms are included during empirical model building for surface roughness. The degree of contribution, as stated in Table 6, developed by using ANOVA Table 8, reveals that speed, feed and depth of cut has 65.10%,19.1% and 2.1% contribution, respectively, in surface roughness. Larger FAo value 19.90 indicates that the variation of the process parameter makes a big change on the surface roughness.

In the ANOVA Table 9 for surface roughness without nanofluids, speed, feed and depth of cut are significant at a 95% confidence level. Therefore, effects of the control parameters are statistically significant at 95% confidence level. The value of R^2 for surface roughness is 0.7958, which signifies that the model can reasonably explain 79.58% of the variability in surface roughness. The high R^2 value indicates that the better model this fits the data. The R^2 adj for the model is 0.6426, which is very close to the value of ordinary R^2, i.e. 0.7958. Thus, it can be stated that no non-significant terms are included during empirical model building for surface roughness. The degree of contribution, as stated in Table 6 developed by using ANOVA Table 9, reveals that speed, feed and depth of cut has 58.38%, 5.87% and 15.35% contribution, respectively in surface roughness.

The effect of cutting speed and feed with and without nanofluids is shown in Fig. 6. These figures indicate that surface roughness increase with increase in speed.

Table 9 shows the results of ANOVA for the surface roughness without nanofluids

Machining parameters	Degree of freedom (f)	Sum of Squares (SS_A)	Variance (V_A)	FA_o	P	Contribution (%)
Speed	1	0.021012	0.021012	11.44	0.028[a]	58.38
Feed	1	0.002113	0.002112	1.15	0.344	5.87
Depth of cut	1	0.005513	0.005513	3.00	0.158	15.35
Error	4	0.007350	0.001837			20.4
Total	7	0.035987				100

S=0.0428661, R^2 =79.58%, R^2 (adj)=64.26%

[a] Significant

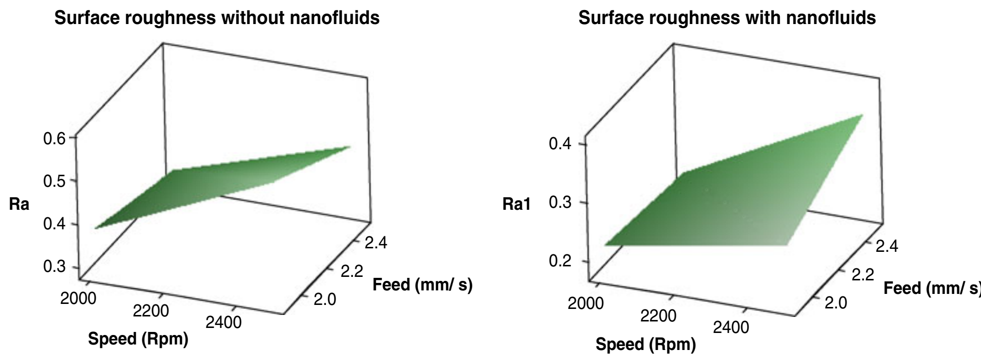

Fig. 6 Response surface of with (*right*) and without (*left*) nanofluids

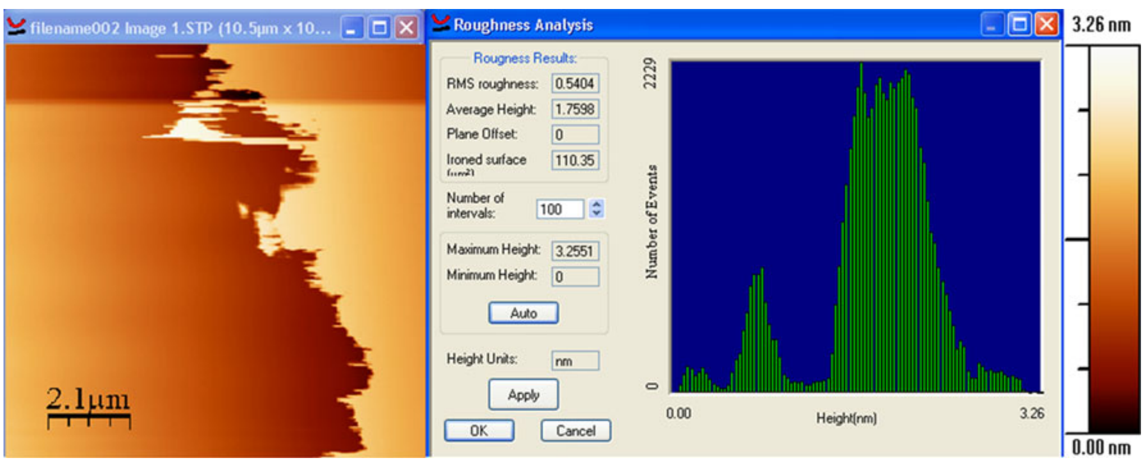

Fig. 7 AFM image of surface roughness for 2,000 rpm cutting speed without carbon nanotube

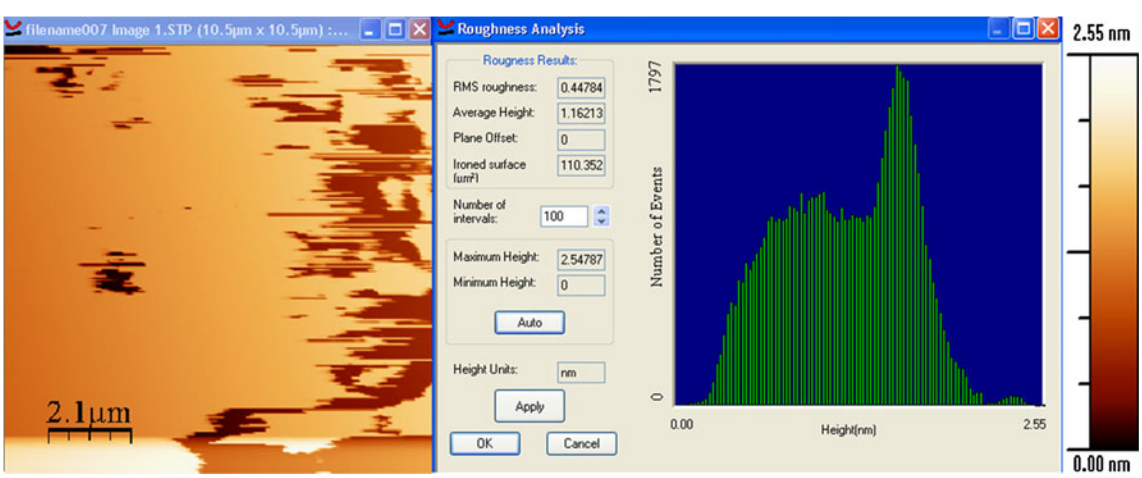

Fig. 8 AFM image of surface roughness for 2,000 rpm cutting speed with carbon nanotube

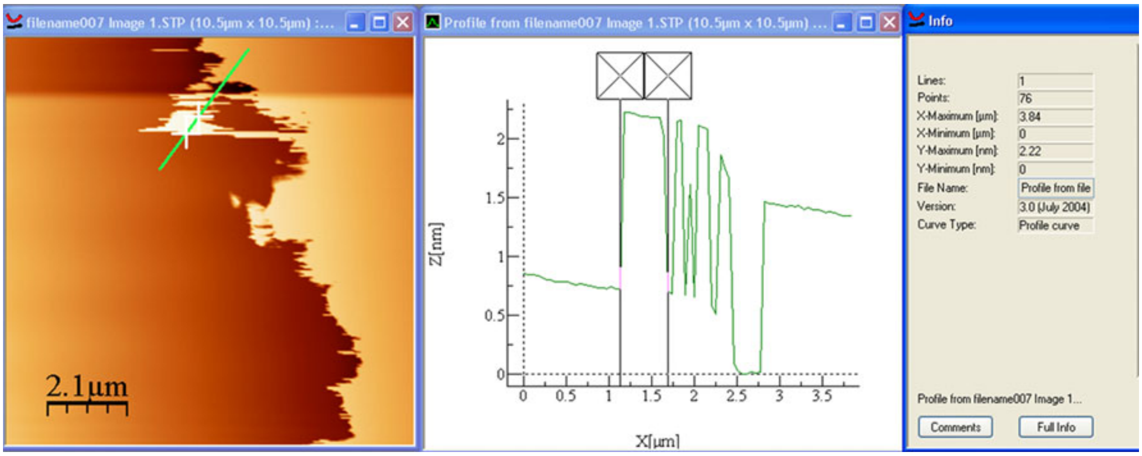

Fig. 9 AFM image of micro cracks for 2,000 rpm cutting speed without carbon nanotube

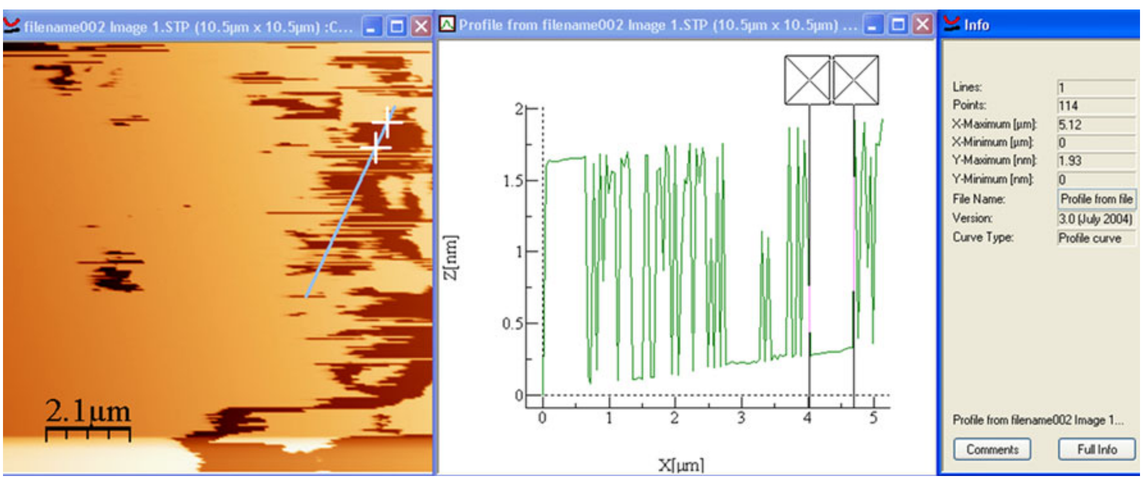

Fig. 10 AFM image of micro cracks for 2,000 rpm cutting speed with carbon nanotube

Table 10 Comparison results of surface roughness

Sample	Surface roughness (μm)	Maximum micro cracks (nm)
Without CNT-based nanofluids	0.5404	2.22
With CNT-based nanofluids	0.4478	1.93

2.4 Surface roughness

To determine the effect of the grinding process on the surface roughness of the AISI D3 tool steel, the surface profiles of the grinding specimens were measured by AFM. The average surface roughness, Ra, of the machined specimen was calculated from the AFM surface topographic data in a scanning area of 10.5×10.5 μm.

The parameters used are cutting speed of 2,000 rpm, feed of 1.9 mm/rev and depth of cut of 0.2 mm without using carbon nanotube as cutting fluids. The roughness value obtained for the specimen without using CNT is 0.54045 μm.

The parameters used are cutting speed of 2,000 rpm, feed of 1.9 mm/rev and depth of cut of 0.2 mm with using carbon nanotube as cutting fluids. The roughness value obtained for the specimen with using CNT is 0.44784 μm.

From these results, it is clear that the specimens machined using nanofluids exhibit better surface finish as compared to specimens machined without using nanofluids. Moreover a higher speed and feed cause a poorer surface finish. In comparing the results of Figs. 7 and 8, it was found that an excellent machined finish can be obtained by adding CNTs to cutting fluids and setting the machine parameters at an optimum speed and feed.

2.5 Micro cracks

Micro cracks of the specimen with and without using carbon nanotube as the cutting fluids shown in Figs. 9 and 10 (Table 10). It is clearly observed that the depth of micro crack Z value is very less compared to without using CNT. The high speed is used in grinding process means that the high micro cracks occurs than at optimum speed used.

$$D\max = H\max - H\min = 2.22 - 0 = 2.22 \text{ nm} \qquad (14)$$

From Fig. 9, 10.5×10.5 μm size of the specimen and depth of focus 2.1 μm of the specimen is scanned by AFM Si tip of 0.2 to 0.5 nm diameter is made to move over the top surface of the AISI D3 tool steel and obtained the morphology image. The figure represents micro crack occurs over the x axis of work piece. The two different colours of dark brown and light brown spread across the surface while in Fig. 10 with CNTs the light brown spread across the specimen and dark brown appears as very small area. The maximum width of the micro crack for without CNTs is more than that with CNTs and 3D morphology clearly shows the micro crack. This is because good thermal property of CNT will absorb heat produced by grinding process and CNT reacts with top layer of the tool steel and reduced crack formation, so that material influence to improve the die material finish. It is clear that the specimens machined using CNTs have better surface finish and reduced maximum micro cracks as compared with the specimens machined without using CNT nanofluids.

3 Conclusion

The mixture of SAE20W40 oil with multiwall carbon nanotubes shows that a clear increase in flash and fire point before and after the addition of nanoparticles. It shows that there is a significant improvement in thermal property. Due to increase in surface area to volume ratio of nanofluids particularly the variation of viscosity in high temperature region is less for nanofluids. The developed empirical formulae can be used to evaluate the surface roughness produced by grinding machining with nanofluid and also with low prediction errors. Furthermore, the AFM application yielded information about the depth of the micro cracks which is important in the post treatment of D3 tool steel machined by grinding process. Thus the surface finish of work piece is elevated to nano level.

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