Research Article

Preparation and evaluation of a stable CNT-water based nano cutting fluid for machining hard-to-cut material

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Abstract

Machining hardened steels is always difficult because of its excessive heat generation. That is why, the application of cutting fluid in machining hardened steel is noted for eliminating defects triggered by the high cutting temperature. In this respect, the aim of this paper is to present a stable high volume carbon nanotube based nanofluid which will act as an efficient cutting fluid and perform better than conventional cutting fluid. To fulfill this purpose, the samples with different volumes of Carbon nanotubes were made and their stability was analyzed. Both the sedimentation and zeta potential analysis proved that the sample made with less than 0.4% volume CNTs shows higher stability. Conventional cutting fluid was made with oil mixed in water and compared its properties to all nano fluid samples. All the nano fluid samples showed higher thermal conductivity and lower viscosity than conventional cutting fluid. Furthermore, a milling operation on 42CrMo4 hardened steel material was performed without any fluid, with conventional (Aquatex 3180 oil based cutting fluid) and with nano fluid. Nano fluid was delivered internally to the cutting zone by using a specially designed liquid applicator. Maximum 29% reduction in cutting temperature, 34% reduction in surface roughness, 33% reduction in cutting force and 39% reduction in tool wear was obtained by using the 0.3 vol% nanofluid sample. So, it can be concluded that the 0.3% volume carbon nanotubes based cutting fluid is an appropriate choice to be used in machining hardened materials.

Keywords Carbon nanotube · Cutting force · Cutting temperature · Milling · Nano fluid · Sedimentation · Surface roughness · Thermal conductivity · Tool wear · Viscosity · Zeta potential analysis

1 Introduction

Hardened steels are known as difficult to cut materials and machining of these materials is known as hard machining. This is hard because while machining tool needs to remove material from the work piece which are over 45 HRC [1]. That is why excessive heat generation and high cutting temperature are the most common and unwanted phenomena in manufacturing industry, especially for machining difficult-to-cut materials [2, 3]. Even this excessive heat generation and its loss into the environment is responsible for ecological damage in environment – a concern for researchers as well as for the industrial personnel [4]. If this heat can be reduced, then problems like surface roughness, tool wear and higher cutting force will be alleviated [5]. To fulfill this purpose the use of a good cutting fluid during a machining operation is very essential. Good cutting fluid must have properties like non-toxic, nonflammable, long term stability, high thermal conductivity and low viscosity to permit the chips washed away quickly from work-tool surface [6]. However, conventional cutting fluids make with mineral oil causes many environmental

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issues and also adversely affect the health of user [7]. These conventional cutting fluids also hamper the health of workers. The concept of dry machining can be a solution of these problems but it always does not show a greater result in terms of surface finish of final work piece [8]. That is why, in recent years, researchers have been investigating the suspension of nano particles to make an efficient cutting fluid [9].

Nanofluids in machining have gained a renewed interest because of their exceptional cooling properties. Nano fluids are made up of dispersion of nanoparticles (1–100 nm) with the base fluid which makes it exceptional than conventional cutting fluids [10]. These nano particles increase contact angle and surface to volume area in the same concentration. Thus, nano fluids provide higher thermal conductivities than conventional cutting fluids—(a) excellent stability, (b) excellent wettability and (c) little penalty due to an increase in pressure drop and pipe wall abrasion experienced by suspensions of millimeter or micrometer particles [11]. Nanoparticles of materials such as metallic oxides (Al_2O_3, CuO, TiO_2), fullerene, nanodiamond, nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors (TiO2, SiC), single, double or multi walled carbon nanotubes (SWCNT, DWCNT, MWCNT), alloyed nanoparticles ($Al_{70}Cu_{30}$) etc. have been used for the preparation of nano fluids. Among them carbon nanotube (CNT) has been considered as an excellent nano particle because they have maximum thermal conductivity (3000 W/m K) than any other nano particles used so far. Moreover, the CNT-water nano-fluid has more thermal conductivity than any conventional base fluid [12–14]. Krishna et al. [15] applied multiwalled CNT-water based nanofluid in Turning EN48 with cemented carbide tool and proved that nano cutting fluid reduced the tool wear and surface roughness. Nano particles in lubricant reduce the friction force by reducing the contact area of two rough surfaces [16]. Many researchers have reported that the use of nano fluid while machining helps to diminish the cutting force and surface roughness [9, 17]. Huang et al. [18] used MWCNT/MQL lubrication in milling SKD 11 die steel and concluded that carbon nanotubes prevent tool wear by increasing wear resistance.

Apart from all these advantages of CNT based cutting fluid one problem has always been raised that CNT is difficult to disperse in water [19]. Because of the inherent Van der Waals forces between carbon particles and very large nonreactive specific surface areas severe sedimentation happens and it deteriorates the quality of cutting fluid [20]. Moreover, fast agglomeration of CNT particles prevents the smooth flow through the pipe and decreases the thermal conductivity of nano fluid [21]. That is why to get the best heat transfer performances, preparation of homogeneous and long-term stable suspensions is important [22]. Water soluble surfactant can be used to increase the stability of nano particles [23]. Many researchers have used the sodium dodycyl sulfate (SDS) as surfactant to produce stable CNT-water suspensions by reducing the surface tension [24, 25]. They concluded that compared to other surfactants SDS shows more stability and less loss of thermal conductivity. However, using the right amount of surfactant is very important to keep the thermal conductivity high.

To produce an efficient CNT based cutting fluid, proper dispersion of carbon nanotubes in the base fluid is very important. Most of the researchers have used ultrasonication methods to disperse carbon nanotubes in a base fluid [14, 18, 26, 27]. Krishna et al. [15] used both magnetic stirring and sonication methods to detach the carbon nanotubes and found a stable suspension. It is to be noted that the duration of magnetic stirring and ultrasonication is a crucial factor that affect the thermal conductivity of the fluid [28].

Review of studies shows that more research is needed to examine the settling problems while using large volume of CNT particles especially in water so that more advantages can be obtained by using CNT based cutting fluid in machining hard-to-cut materials [26]. In the present work, four samples have been prepared with different volume of CNT particles and analyzed for stability, thermo-physical properties to find out the efficient cutting fluid. This study finds an optimum ultrasonication time and surfactant quantity to prepare a stable cnt-water based nanofluid. Also, the effect of inclusion rate of CNT particles on sedimentation, zeta potential, thermal conductivity and viscosity has been discussed here.

2 Preparation of samples

The first step in the work was the preparation of the nano fluid and conventional cutting fluid. CNT was used as the nanoparticles (Single walled, < 30 nm) procured from the Tanfeng Tech company, USA. It was produced as dry powder by chemical vapor deposition (CVD) method with density of 1.6 g/cm^3.

Figure 1 shows respectively the scanning electron microscopy images of the carbon nanotubes at 100 nm scale. It reveals that the diameter of the nanotubes is not more than 30 nm. Four nanofluid samples of different volume percentages (0.2, 0.3, 0.4 and 0.5%) were prepared by dispersing different quantity of CNT nanoparticles in 150 mL deionized water (Table 1). In an earlier study Andhare et al. [26] found that sedimentation occurs quickly with a concentration of more than 0.1%. To improve this situation in the present study this particular percentages were selected.

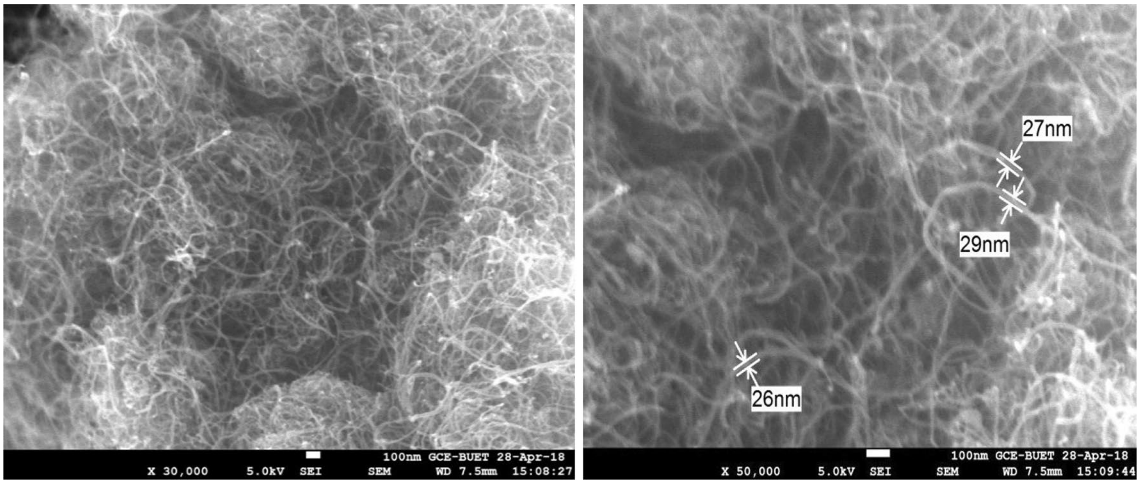


Fig. 1 SEM image of Carbon Nano tube

Table 1 Weights of CNT NPs required in preparing the nanofluids of different volume concentrations

Weights of CNT nanoparticles (g)	Volume concentrations of nanofluids (vol%)
0.30	0.2
0.45	0.3
0.60	0.4
0.75	0.5

At first, the magnetic stirring was used to prepare a good blend of carbon nanotubes in base fluid. However, it is to be noted that the magnetic stirring solely cannot disperse CNTs in deionized water. Therefore, the ultrasonication was needed to produce sufficient distribution and acceptable homogeneity. This is a commonly used method in the preparation of nanofluids because it exerts sound energy to break the agglomeration and increase the dispersion of nanoparticles.

All samples were made by using JSHS-18D Digital hotplate magnetic stirrer and ultrasonicator (power sonic 510, Capacity: 10 L). While stirring there was no supply of heat and stirring speed was 1500 rpm. During ultrasonication, energy is produced to agitate the carbon nanotubes but some of the energy dissipates as heat energy which increases the temperature of fluid [29]. In this case, the temperature in ultrasonicaion process was increasing exponentially with time and the range was kept 25–75 °C to avoid vaporization. Cycle of 30 min ultrasonication was used and the frequency was always kept 40 kHz during sonication. Magnetic stirring and ultrasonication of all samples were done repeatedly till stable dispersion was observed and also concurrently so that there is no resting time of any sample.

First the nanotubes were not dispersed in deionized water by stirring and being precipitated in only 5 min after preparation, leaving the upper fluid transparent. This happens because hydrophobic surface of carbon nanotubes creates strong van der Waals bond among the nanoparticles to coagulate with each other. As a solution of this problem, researchers recommended that the surfactant can be used to transform the surface into hydrophilic state from hydrophobic state. Thus the adhesion behavior of nanoparticles will be changed and agglomeration will be reduced [28, 30]. Andhare et al. [26] reported that adding 0.5 vol% SDS as surfactant can not make stable solution with cnts more than 0.1 vol%. Therefore, in this work 0.6 vol% water soluble Sodium dodecyl sulfate [$CH_3(CH_2)_{10}CH_2OSO_3Na$] was added in powder form as surfactant to all samples of CNTs while stirring to improve the dispersibility of the added CNTs. Adding more SDS can increase foaming in the cutting zone while machining. That is why the amount of SDS was limited to 0.6 vol% for the present work.

The amount of SDS (0.6 vol%) was decided to keep higher than the amount of CNTs in every sample. Sodium dodecyl sulfate acted as a good surfactant by reducing the surface tension of carbon nanoparticles and increasing the dispersion of particles in the base fluid.

Conventional cutting fluid consisted of 10% (volume) of Aquatex 3180 general purpose milky soluble oil mixed in water and has a density of 0.89 g/cm^3. Aquatex 3180 shows the high stability when mixed with water and commonly used in various types of machining operations.

3 Measurements

3.1 Sedimentation

Sedimentation is a method which has been used by many researchers to observe the stability of nano particles in the base fluid [31]. Gajrani et al. [32] used five concentrations (0.1–0.5%) of molybdenum disulfide (MoS_2) nanoplatelet and calcium fluoride (CaF_2) to develop different hybrid nano green cutting fluid samples and showed that 0.3 vol% MoS_2 based fluid possessed higher thermal conductivity, viscosity and specific heat than any other sample of nanofluid. Here, all of the four samples of nanofluids at different CNT concentrations were prepared by 1 h magnetic stirring following 1 h ultrasonication and was kept inside the transparent test tubes in a completely steady condition to make a visual inspection for 7 days. The Fig. 2 shows that only sample with 0.2 vol% CNT and sample with 0.3 vol% CNT show stability after 72 h (3 days). The CNT particles of sample with 0.4 vol% CNTs and 0.5 vol% CNTs started settling after 48 h (2 days).

Again, four samples have been prepared using same CNT weight percentages, but this time ultrasonication period was increased from 1 to 1.30 h with 1 h magnetic stirring. The increment of ultrasonication time was decided by trial and error method. Stability was stared to be observed in all the samples after increasing the ultrasonication time by 30 min. But after 3 days, the nanotubes of sample 0.5 vol% had a large and considerable amount of precipitation. However, the rates of precipitation in the sample which was made by 0.4 vol% of CNT were less than previous observation and was not showed any settlement before 7 days. Also, sample made of 0.2 vol% and 0.3 vol% CNTs was not shown any major sedimentation even after 7 days of preparation.

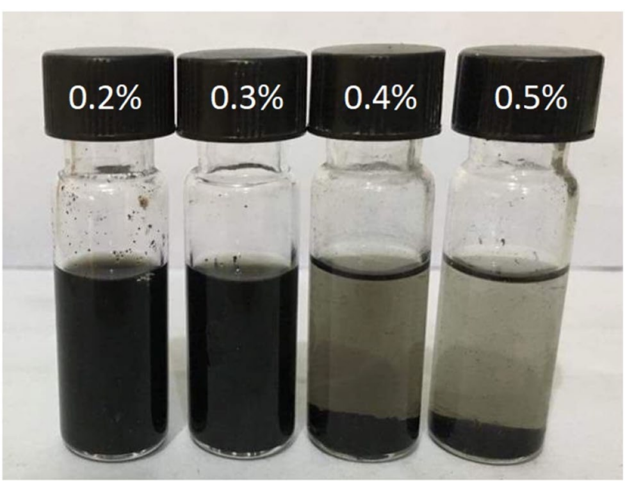
Figure 3 reveals that sonication time can affect the dispersion of nanotubes inside the deionized water. Reportedly, an increased sonication time can provide more amount of energy which is required for separating carbon nanotubes in the base fluid [33].

3.2 Zeta potential analysis

Many researchers executed zeta potential analysis for detecting acceptable stability of nanofluids [34–36]. The higher zeta potential value of suspensions is considered to be more stable than the suspensions with low zeta potential value.

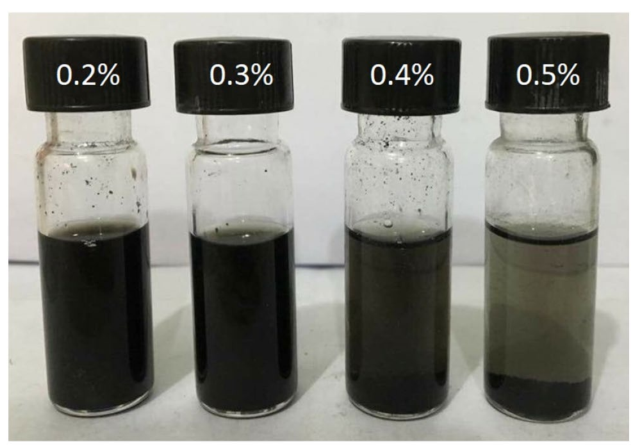
In this study also, stability of all the samples were investigated by using the Zeta potential analysis method. Zetasizer Nano (Malvern) was used to measure zeta potential value of nano fluid samples. Both electrophoresis and laser Doppler velocimetry techniques were used for this measurement. Afterward, the most known and widely used theory Smoluchowski equation was used for calculating the Zeta potential from the measured mobility for the nanoparticles in deionized water [37].

A reusable capillary cell that was available with instrument was filled with 0.75 mL of freshly prepared sample. The cell had two gold plated electrodes and voltage was applied to the sample to create movement among the particles underneath of an amplified field. Cell was inserted into the holder and lid kept closed. Machine was in automatic mode and temperature was 25 °C. After 300 s the ZS Xplorer software displayed a graph with the value of



Four samples after 72 hours observation

Fig. 2 Photographic View of Samples made by 1 h magnetic stirring + 1 h ultrasonication



Four samples after 7 days observation

Fig. 3 Photographic view of samples made by 1 h magnetic stirring + 1.30 h ultrasonication zeta potential and light intensity. The graph showed one peak at 26.7 mV in area 100% for sample 0.2 vol%. Thus zeta potential value of each sample was measured for three times and the average value is presented in Table 2. A graph has been plotted in Fig. 4 with these values to compare which sample has a higher zeta potential value.

3.3 Thermal conductivity

Higher thermal conductivity is a vital property of being an efficient cutting fluid. Consequently, it is important to measure the thermal conductivity of the prepared fluid. Different ways and experiments have been designed by researchers to find the accurate thermal conductivity of nano fluids.

In this study, the Hilton thermal conductivity unit has been used to measure the thermal conductivity of nanofluids and conventional cutting fluid. It is proved to be a successful apparatus to determine thermal conductivity [38]. Plug/jacket assembly and console are the two parts by which this unit is developed. There is a small radial clearance between the plug and jacket which was filled by a particular sample fluid using a syringe to determine fluid thermal conductivity. At the time of measurement, the plug was heated by an electrical heating element through an aluminum section and the jacket was cooled by water.

There is one water inlet and outlet section to provide an isothermal boundary section. There are two "O" rings which provide a sealing between water and working fluid surface. Temperature of water and fluid were measured by thermocouple and variable transformer was used to provide a variable voltage. At first, a certain voltage was selected and then the setup was allowed to achieve a constant temperature. When the reading become stable, then the temperature value of plug and jacket was collected to calculate thermal conductivity of the sample for that particular temperature. Thus different temperature such as, 60 °C, 70 °C, 80 °C and 90 °C was obtained by setting the voltages accordingly. 20–50 °C were the common range of temperatures used by researchers while measuring the thermal conductivity of nanofluids [39]. But in this study, the attempt was to measure thermal conductivity of the samples at possible higher temperatures as the machining temperature. Before using the unit to determine the thermal conductivity of samples, it has been calibrated with a test fluid (air) and a graph between ΔT and Q_i has been drawn. Then, the thermal conductivity of deionized water has been measured and compared with data in the literature. Finally, the thermal conductivity of the samples was measured at four different temperatures by, $k = \frac{Q_c \Delta r}{A \Delta t}$,

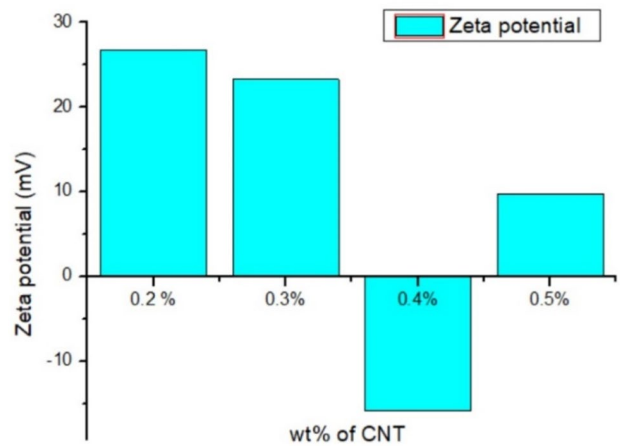


Fig. 4 Zeta potential analysis of CNT based nano fluids

Table 2 Zeta potential values of all samples

Sample nos.	Samples (vol%)	Zeta potential (mV)	Zeta deviation (mV)
1	0.2	26.7	6.34
2	0.3	23.3	5.89
3	0.4	− 15.8	5.33
4	0.5	9.76	5.21

Table 3 Thermal conductivities of all nanofluid samples and conventional cutting fluid

Sample nos.	Samples	Temperature (°C)	Thermal conductivity (W/m k)
1	0.2 vol%	60	1.15
		70	1.28
		80	1.37
		90	1.49
2	0.3 vol%	60	1.21
		70	1.33
		80	1.42
		90	1.52
3	0.4 vol%	60	1.25
		70	1.36
		80	1.43
		90	1.53
4	0.5 vol%	60	1.28
		70	1.38
		80	1.44
		90	1.54
5	Conventional cutting fluid	60	0.98
		70	1.01
		80	1.05
		90	1.10

W/mK. Here, Q_c is the heat transfer by conduction through the fluid sample, Δr is the radial clearance, A is the effective area of conducting path through fluid and Δt is the temperature difference of jacket and plug surface temperature (Table 3).

3.4 Viscosity

Viscosity is one of the most important parameters of nano fluids to prove that the prepared nanofluids will have potential applications as coolants in advanced thermal systems. So in this research, the attention was focused on measuring and evaluating viscosity of nano fluid samples with conventional cutting fluid. The saybolt universal Viscometer is the most commonly used device to measure the viscosity of a fluid. Ozbey measured the kinematic viscosity of the Al_2O_3/water nanofluids by using Saybolt viscometer [40]. As such, Saybolt universal viscometer setup has been selected to determine the kinematic viscosity of the CNT/water nanofluids in units of Saybolt universal seconds (SUSs) and converted the SUS units to centistokes (Table 4).

The apparatus consists of a standard fluid tube which is provided at the top with an overflow cup. At the bottom a small outlet orifice (Diameter-0.176 cm and Length-1.225 cm) is enclosed through which the nano fluid flows into a 60 cc container. The sample of fluid was kept vertically in a bath and bath was equipped with a heater to raise the temperature of fluid. The stopwatch was used to observe the time taken by the fluid to fill up a 60 cc container. Before measuring the viscosity of nano fluid samples, the viscosity of water was measured and compared with the data in the literature. Then after validating the setup, the kinematic viscosity of conventional fluid and nano fluid samples was determined at the same temperatures (20 °C, 30 °C, 40 °C and 50 °C) on which thermal conductivities were measured using the following equation:

$$\textit{Kinematic viscosity}, v = 0.220t - \frac{135}{t}$$

Table 4 Kinematic Viscosities of all nanofluid samples and conventional cutting fluid

Sample nos.	Samples	Temperature (°C)	Saybolt universal seconds, t (s)	Kinematic viscosity, v (Cst)
1	0.2 vol%	60	26.005	0.53
		70	25.791	0.44
		80	25.673	0.39
		90	25.509	0.32
2	0.3 vol%	60	26.069	0.557
		70	25.922	0.495
		80	25.728	0.413
		90	25.572	0.347
3	0.4 vol%	60	26.163	0.596
		70	26.00	0.528
		80	25.829	0.456
		90	25.693	0.398
4	0.5 vol%	60	26.302	0.654
		70	26.156	0.593
		80	25.962	0.512
		90	25.796	0.442
5	Conventional cutting fluid	60	27.098	0.98
		70	26.975	0.93
		80	26.827	0.87
		90	26.729	0.83

4 Selection of nanofluid

Higher stability is very important factor for being a good quality cutting fluid. Less stability can result in clogging in case of microchannels and also in the decreasing of thermal conductivity of nanofluids. So, after preparation of different samples, stability and thermo-physical properties of nanofluids have been analyzed for understanding which sample should be selected for machining application.

4.1 Analysis of stability

Stability is an important issue to enhance the properties of nanofluids for application [21]. There are different types of stability evaluation methods like sedimentation method, spectral absorbency analysis method and Zeta potential analysis. For the present study, both the sedimentation method and Zeta potential analysis have been used to evaluate the effect of nanotube concentration on the stability of CNT-water based nanofluids.

Sedimentation process has been tested in room temperature (25 °C) and revealed that 0.4 vol% and 0.5 vol% of nanofluid are unable to stay stable for 72 h, whereas 0.2 vol% and 0.3 vol% stay stable even after 7 days. When the ultrasonication time has been increased to 1.30 h 0.4 vol% also start showing more stability than before. The reason behind this result can be explained by the effect of ultrasonication time. Higher ultrasonication time showed a positive impact on the sample that was made with a higher carbon percentage (0.4 vol%) by providing more energy to disperse the particles. The time of ultrasonication (1.30 h) and magnetic stirring (1 h) during the preparation of all the samples were same, nonetheless it is proving to be optimum only for samples that was made with CNTs lesser than 0.5 vol%. Further increased in ultrasonication time on surfactant quantity may result positively for sample having more CNTs than 0.4 vol% but it is also needed to remember that prolonged ultrasonic time formed amorphous carbon by fragmenting and also decomposed the surfactants into complex structures, thus sedimentation rate can be increased. Determining the optimum amount of surfactant is very important as small amount of surfactant can not create stable nanofluid on the other hand, large amount of surfactant can also decrease the stability because of self-agglomeration effect of SDS particles [41, 42]. So, trial and error method is needed to find out the optimum percentage of surfactant that should be used. However, the graph (Fig. 4) of zeta potential proves that sample made of lesser 0.4 vol% CNTs is better in stability because of exhibiting higher value than the sample made of 0.4 vol% and 0.5 vol% CNTS. This is because the amount of surfactant used (0.6 vol%) was not optimum for samples with 0.5 vol% CNT. A negative zeta potential value was noticed for 0.4 vol% sample. From the point of view of physics, the (−ve) anionic surfactant causes −ve potential. As sodium dodycyl sulfhate is negatively charged surfactant and has not dissolved properly in the sample that is why positive charge of the ions was absorbed by the negative ones. As a result negative value of zeta potential has been shown. When the amount of CNT rises in the sample there is a narrow space for nanoparticles to disperse in a base fluid [28]. As a result, a lower value of zeta potential was obtained for sample made of 0.5 vol% CNTs. The used ultrasonication time and surfactant quantity were found optimum for sample made of lesser 0.4 vol% CNTs and thereby it showed the best result in both sedimentary and zeta potential test.

4.2 Analysis of thermo-physical properties

The thermal and physical properties of freshly prepared nano fluids have been investigated by evaluating both thermal conductivity and viscosity of nanofluids. The thermal conductivity of conventional cutting fluid and nanofluid samples containing different weight percentages of CNTs such as 0.2 vol%, 0.3 vol%, 0.4 vol% and 0.5 vol% was measured and the experimental results were plotted on a graph against temperature. It has been found that the conventional fluid has lower thermal conductivity than any other nano fluid samples. The Fig. 5 also shows that the thermal conductivity of nanofluids linearly increased for different volume concentration such as 0.2%, 0.3%, 0.4% and 0.5% with a corresponding increase in temperature of nanofluids from 60 to 90 °C. Thermal conductivity also found to be increased with the increasing amount of CNTs. This same trend was also observed by Andhare et al. [26]. These linear relationships were obtained because the high temperature and CNT percentages increase Brownian motion and surface-volume ratio of CNTs accordingly. Thus, it creates collisions and interaction between the

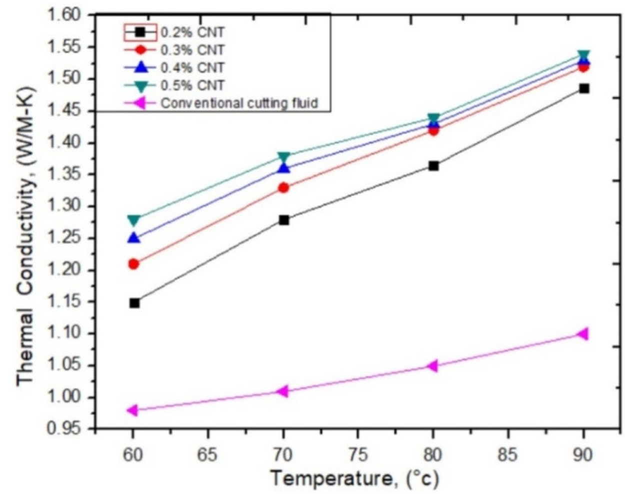


Fig. 5 Variation of thermal conductivity for CNT nanofluids with different temperature

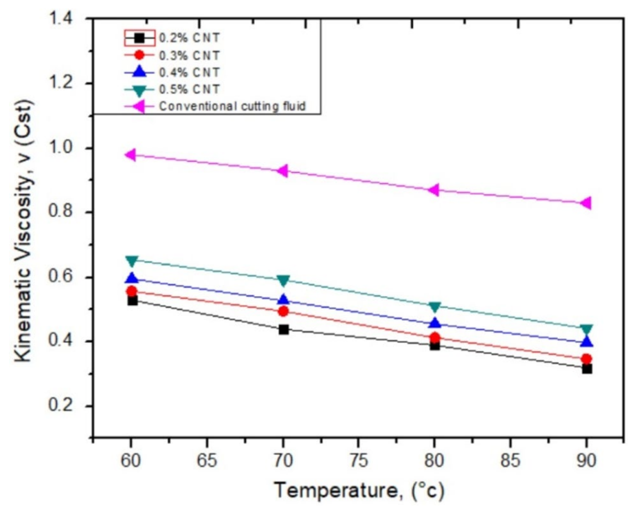


Fig. 6 Variations of Kinematic viscosity for samples at different temperature

particles which helped to enhance the thermal conductivity [43]. One thing is noticeable from the result of the present experiment that although sample was made of 0.5 vol% contained more amount of CNTs, it shows a little increment with time in thermal conductivity than sample of 0.2 vol% and 0.3 vol%. However, 0.2 vol% and 0.3 vol% showed a remarkable growth compared to the thermal conductivity of sample 0.5 vol%. Hence, it cannot be ignored that a good dispersion and stability of nanoparticles is imperative to obtain high heat conduction.

For the purpose of showing the effect of concentration of carbon nanotubes and temperature on viscosity of fluids, a graph in Fig. 6 was plotted with the kinematic viscosity of nanofluids (0.2, 0.3, 0.4 and 0.5 vol%) in the ordinate and temperature at its abscissa. At 60 °C, water's kinematic viscosity is 0.465 cst. From the value of the sample's kinematic viscosity it is clear that at high temperature like 80 °C they act as water, which is much needed to become a good cutting fluid. It is observed from Fig. 6 that the viscosity of conventional cutting fluid is much higher than that of nanofluid samples. It also reveals that the viscosity had an linear increasing trend with increasing concentration of carbon nanotubes and decreasing trend with temperature. The possible reason for this behavior is increased shearing action of molecules with increasing weight percentages of CNTs. However, the high temperature initiates distraction between these particles which results in a lower viscosity [43].

After the analysis, the sample with 0.3 vol% CNTs was selected for further machining experiments as it had shown higher stability, good thermal conductivity and lower viscosity. Also, no previous study had used 0.3% CNT-water based nanofluid for milling hardened steel.

5 Machining experiment

Machining hardened steel is always very challenging because it generates high heat in the tool-workpiece interface. That is why for the present investigation a hardened alloy steel like 42CrMo4 steel has been undertaken. This alloy steel is used in manufacturing of gears, crankshafts, connecting rods and also in die industry. Table 5 shows the conditions under which the machining was carried out. During machining a different set of cutting parameters were used as stated in Table 5 for three types of cutting environment such as dry, milling with conventional cutting fluid, milling with nanofluids.

To supply the cutting fluid internally through the milling cutter a specially designed and developed rotary liquid applicator was used as shown in Fig. 7 [44, 45]. This type of setup has not been used before to deliver nanofluid while end milling. The extension part of the adapter was inserted to the spindle of the machine though a collet. The container was attached with the adapter with the help of two

Table 5 Experimental conditions

Machine tool	Vertical knee and column type milling machine, China
Work materials	42 CrMo4 steel (size: 158 × 120 × 35 mm)
Hardness	53 HRC
Cutting tool	HSS End Milling Cutter (Ø16 mm)
Process parameters	
Cutting speed	30, 40, 50 and 60 m/min
Table feed	22, 34, 44 and 52 mm/min
Depth of cut	0.50, 0.75 and 1 mm
Environment	Dry, with conventional cutting fluid and with nanofluid

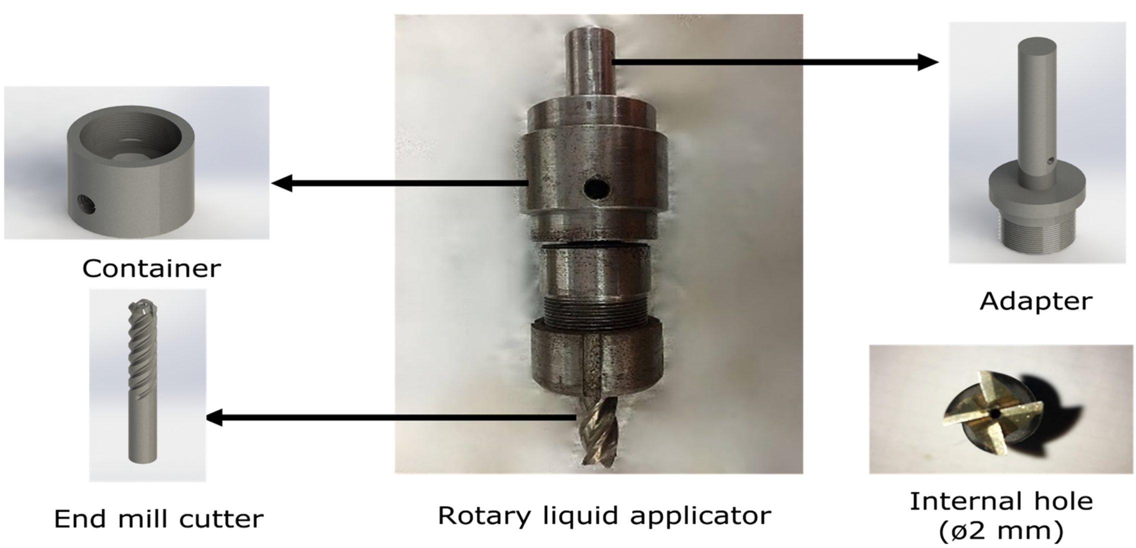


Fig. 7 Different parts of rotary liquid applicator

journal bearings. There is a hole on the container through which a pipe was assembled. Finally, Jam nut was used to hold the cutter within the adapter. The high speed steel (HSS) milling cutter was modified by making internal small hole (Ø2 mm) with the help of electrical discharge machining (EDM) for applying nanofluid directly at the cutting zone. Thus the rotary liquid applicator was designed for internal cooling system.

In the full setup, a compressor was connected to pressure valve and the other side of the valve was connected to a fluid tank as shown in Fig. 8b. The compressor was switched on and pressure gauge was controlled to set the bar of compressed air. The compressed air helped to transfer the fluid from the tank to the cutting zone via rotary liquid applicator and cutter. Pressure gauge was set to 12 bar because at that time the fluid was getting out from the cutter as a splash of air and foam of solution was not produced. More pressurized air creates more foaming in the cutting zone which results in less mobility of the chips leading to increased roughness. The full machining setup and procedure to apply cutting fluid on the work piece is shown in Fig. 9.

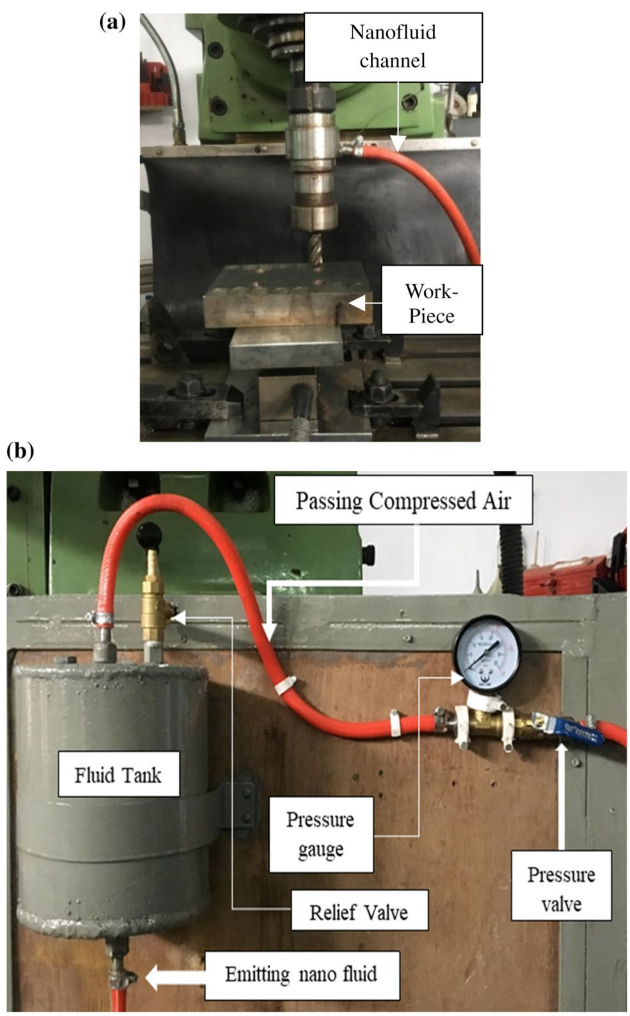


Fig. 8 **a** Photographic view of rotary liquid applicator, **b** fluid tank and its delivery system

6 Machining results

In the present work, surface roughness and cutting force have been investigated to evaluate the relative role of CNT-water based nanofluid in compare to dry milling and milling with conventional cutting fluid at different cutting velocity, table feed and depth of cut.

6.1 Effect of nanofluid on cutting temperature

Work-tool interface temperature was measured using thermal gun in different environments after certain machining time to understand the changes of cutting temperature. Table 6 reveals that in all environments cutting temperature increases with machining time because of the continuous heat generation at the tool and workpiece interface.

The plotted graph in Fig. 10 has shown the reduction of cutting temperature while machining with cnt water based nanofluid. The higher thermal conductivity of the nanofluid carried away the heat from the contact area of the tool and work which lessens the cutting temperature. It was also noticeable that the maimum reduction percentage was obtained when the cutting temperature was high as the thermal conductivity of water based nanofluid increases with temperature.

6.2 Effect of nanofluid on surface roughness

After machining at various cutting speed (V_c), table feed (S_o) and depth of cut (t) combinations under dry, milling with conventional cutting fluid and milling with nano fluid, the surface roughness of the machined surface were measured by a Talysurf roughness checker (Surtronic 3+, Rank Hobson, UK) using a sampling length of 4.00 mm. Then the values of roughness were plotted in a graph as shown in Fig. 11a–c.

It has been observed that surface roughness increased as the cutting speed decreased. This can be a consequence of the fact that lower cutting speed produces vibration which deteriorates surface roughness [46]. Also higher cutting speed induces extra hardness within the material and creates favorable chips which decreases the surface roughness [47]. A positive trend of surface roughness has been noticed with increased both depth of cut and feed rate. Increase in energy input while machining with larger feed rate causes increment in surface roughness [48]. As the

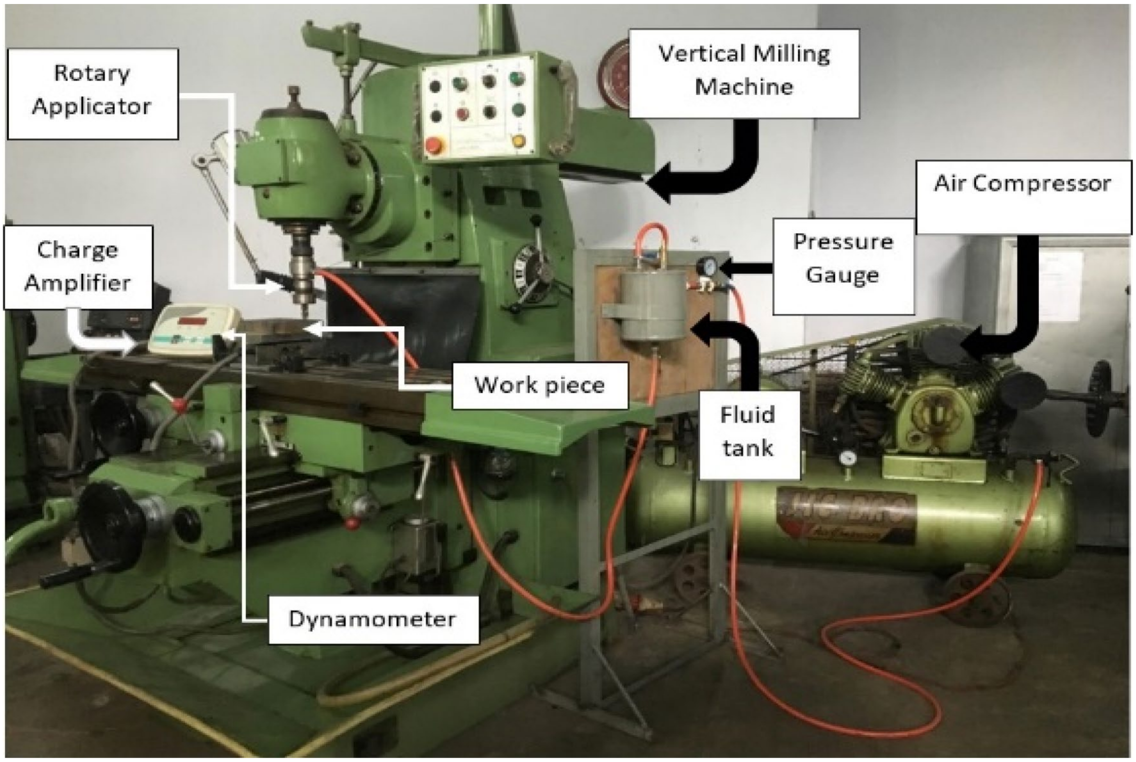


Fig. 9 Photographic view of the experimental set up

Table 6 Values of cutting temperature after various machining time

Machining time	Temperature in dry condition (°C)	Temperature with conventional cutting fluid (°C)	Temperature with nanofluid (°C)	Percentage reduction in cutting temperature	
				Milling with conventional cutting fluid	Milling with nanofluid
30	51.44	46.12	42.59	10	17
60	57.12	51.45	47.09	10	18
90	65.43	58.04	53.08	11	19
120	79.65	71.66	64.78	10	19
180	98.87	88.34	79.19	11	20
240	122.07	105.32	93.65	14	23
300	145.65	122.56	112.87	16	23
432	185.72	158.23	135.76	15	27
540	224.43	189.98	158.5	15	29

depth of cut increases, higher friction and cutting forces occurs which leads to poor surface finish [49].

Also, the obtained average surface roughness values after a certain time at a particular set of cutting parameters (Vc = 40 m/min, So = 44 mm/min, t = 1 mm) under three cutting conditions were listed in Table 7. A graph was plotted for machining time of 10 min in Fig. 12.

The graphs in Fig. 11a–c are showing that the application of nanofluid under different experimental parameters has decreased the surface roughness of work material in a large extent. This results was obtained because of the higher thermal conductivity of nano fluid as it helps to take the heat from the chip-tool interface quickly. Thus it prevents the built up edge formation on the work material which leads to reduction of surface roughness.

Figure 12 shows that roughness linearly increased with machining time under all machining environments. This is because heat at chip-tool interface also rises with time

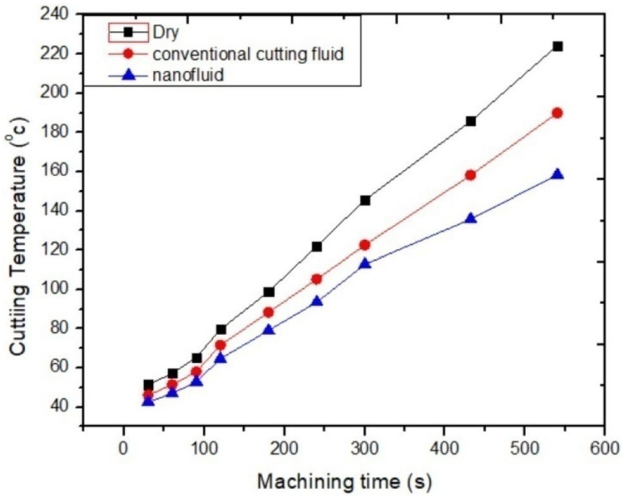


Fig. 10 Cutting Temperature under different cutting environments

which causes greater roughness. Nonetheless it is noticeable that nano fluid has a positive influence on roughness because of having higher thermal conductivity and lower viscosity. Also, nano fluid reduces the friction between tool and workpiece which resulting in lesser temperature, can be attributed for the minimization of the surface roughness while using nano fluid.

6.3 Effect of nanofluid on cutting force

The values of cutting force have been monitored by dynamometer at different cutting velocity, table feed and depth of cut and the effects of nanofluid on main cutting force (P_z) under different machining parameters have been shown in Fig. 13a–c.

Figure 13 represents that cutting force exhibits same trend like surface roughness with various control variables.

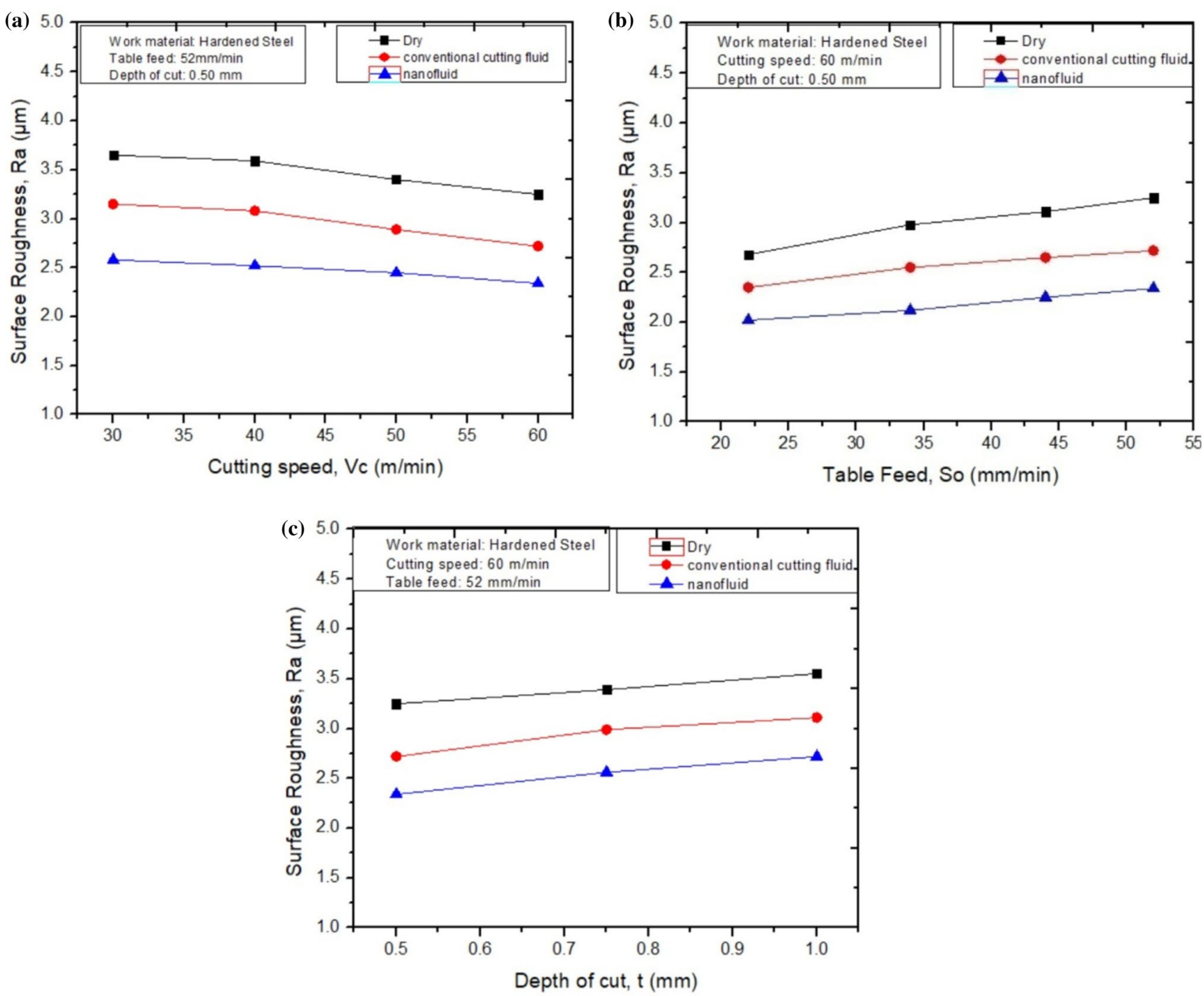


Fig. 11 Effects of different environments on surface roughness (R_a) under a set of **a** Cutting speed (V_c), **b** table feed (S_o) and **c** depth of cut (t)

Table 7 Values of roughness after various machining time

Machining time (s)	Roughness in dry condition	Roughness with conventional cutting fluid (µm)	Roughness with nanofluid (0.3 vol% CNT)	Percentage reduction in surface roughness	
				Milling with conventional cutting fluid	Milling with nanofluid
30	2.21	1.72	1.506	22	32
60	2.26	1.82	1.526	19	32
90	2.38	1.88	1.576	21	34
120	2.42	1.95	1.64	19	32
180	2.49	2.01	1.7	19	32
240	2.58	2.09	1.73	19	33
300	2.65	2.13	1.85	20	30
432	2.76	2.25	1.92	18	30
540	2.88	2.34	1.94	19	33

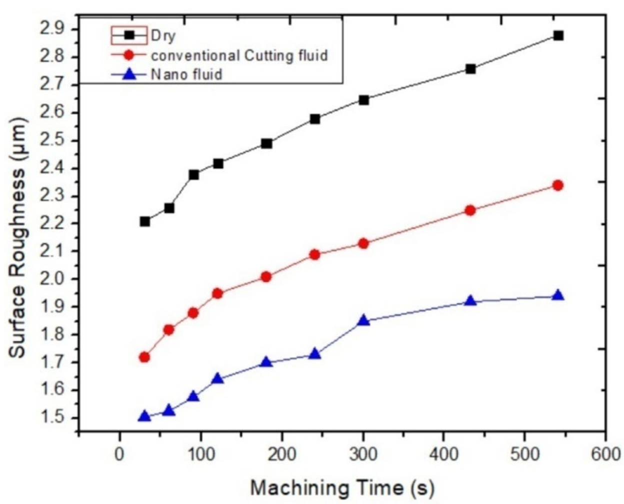


Fig. 12 Surface roughness under different cutting environments

The generated temperature at higher cutting speed softens the material which resulted in lower cutting force, chatter and vibration. Also higher cutting speed blocks the formation of build up edge chips which helps to retain sharpness of the cutting tool and thus reduces cutting force [50]. Increased feed rate increases the material removal rate and causes plastic deformation, increases cutting force [48]. Higher depth of cut rises the contact between tool and material which increases the friction. Higher friction then resulted in higher cutting force [49].

A graph as shown in Fig. 14 was plotted to observe the variation of cutting force at Vc = 40 m/min, So = 44 mm/min, t = 1 mm with the progress of duration of milling. Table 8 and Fig. 14 shows the percentage reduction in cutting force attained by conventional fluid and nanofluid cooling condition during machining for 10 min.

The figures from Fig. 13a to c as well as from Fig. 14 and Table 8 clearly visualize that reduction in the cutting forces by nanofluid happened to be much higher in compared to dry machining and machining with conventional fluid.

Cutting force increases as the friction between chip-tool rises. To minimize this friction, fluid needs to be supplied into the interface of chip-tool. The capillary action of Nanofluid helps to reduce this friction which resulted in lesser cutting force. This narrow penetration capability also helps to reduce heat of tool workpiece interface and thus surface roughness.

6.4 Effect of nanofluid on tool wear

Different types of tool wear (adhesion, abrasion etc.) can be found while milling depending on the work and tool material. In the present investigation mostly gradual wear has been observed by scan electron microscope (SEM). The top view of worn out milling tools is shown in Fig. 15. The growth of tool wear over the machining time is depicted in Fig. 16. In all conditions, tool wear has been increased with machining time due to high temperature between tool-workpiece. Maximum tool wear was found in the dry condition and minimum was obtained while using nano fluid (Table 9).

The generated high heat in the dry condition caused this larger tool wear. As conventional cutting fluid used, the tool wear was found to be reduced at some percentages but not as much as nano fluid because of its poor penetration tendency. Also, nano fluid has high heat transfer capability which helped to retain the strength and sharpness of tool edges. Thus it lowered the friction and temperature which was supposed to generate from this friction [51]. The reduction percentages have been found in the present work for all the outputs (cutting temperature, surface roughness, cutting force, tool wear) is

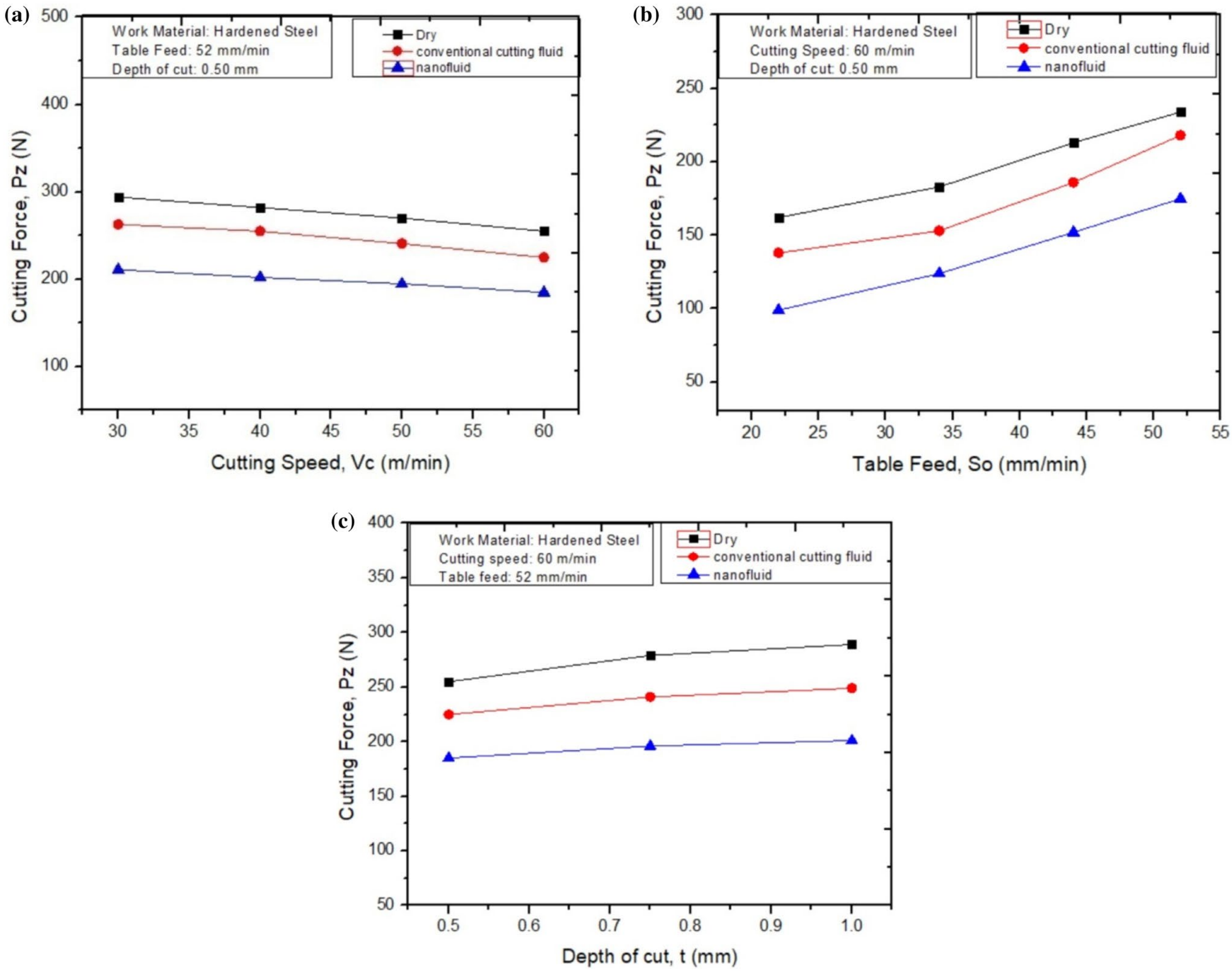


Fig. 13 Effects of different environment on cutting force (Pz) under a set of **a** cutting speed (V_c), **b** table feed (S_o) and **c** depth of cut (t)

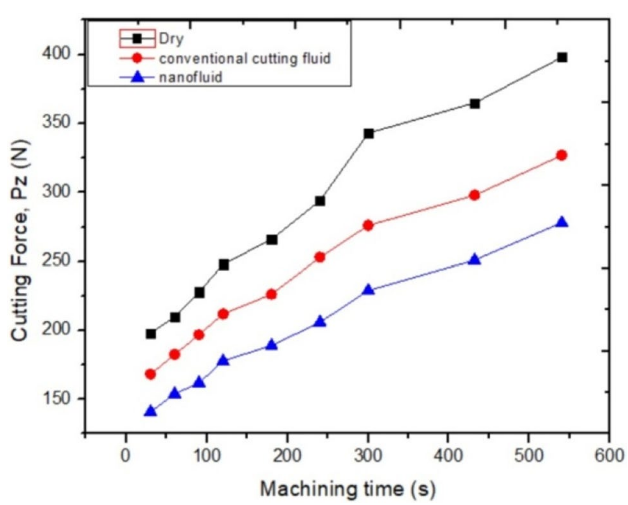


Fig. 14 Cutting Force under different cutting environments

resulted better than other previous researches where cnt based nano fluid was used while machining [18, 27, 51].

7 Modeling of surface roughness and cutting force

Predictive models always helpful in manufacturing industry for forecasting the machining outputs before practically conducting the experiments. It helps to reduce production time and cost which can lead to higher productivity. Different methodologies such as RSM [52], ANN [53], ANFIS [54] etc. have been used to develop predictive models for surface roughness and cutting force. In this work, response surface methodology has been used to develop two quadratic Eqs. (1) and (2) which will help to estimate both surface roughness and cutting force.

Table 8 Values of cutting force after various machining time

Machining time (s)	Cutting force in dry condition	Cutting force with conventional cutting fluid (Pz)	Cutting Force with nanofluid (0.3 vol% CNT)	Percentage reduction in cutting force	
				Milling with conventional cutting fluid	Milling with nanofluid
30	198	168	141	15	29
60	210	182	154	13	27
90	228	196	162	14	29
120	248	212	178	15	28
180	266	226	189	15	29
240	294	253	206	14	30
300	343	276	229	20	33
432	365	298	251	18	31
540	398	327	278	18	30

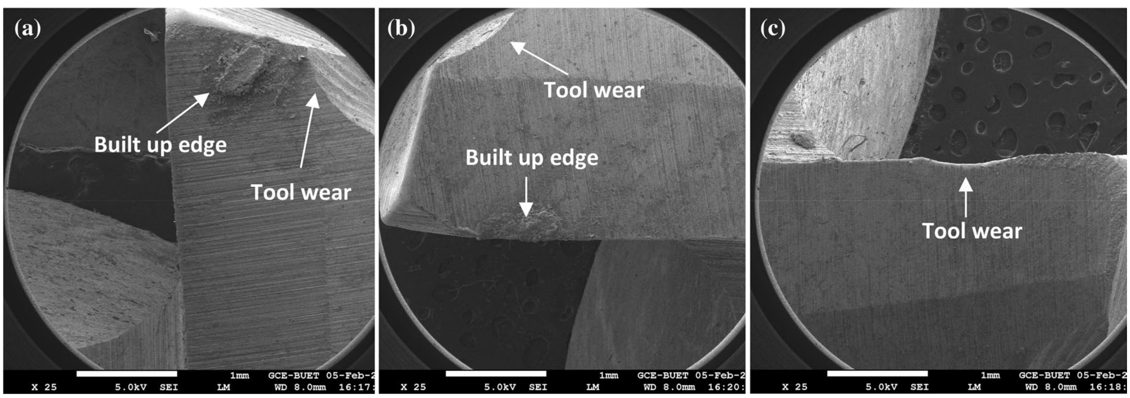


Fig. 15 SEM images of milling cutter after machining (**a**) in Dry (**b**) with conventional cutting fluid (**c**) with machining nanofluid

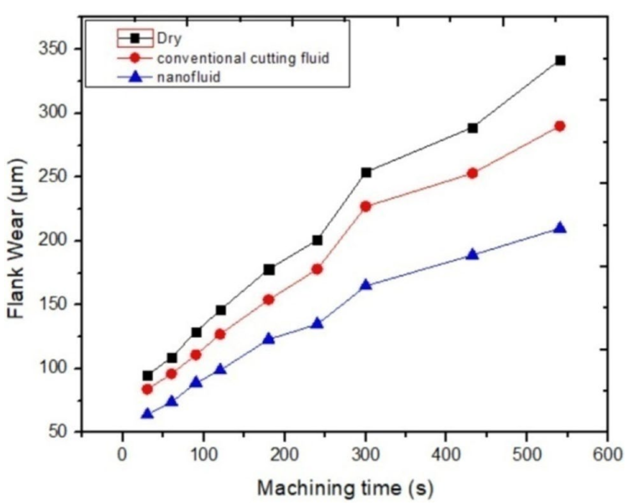


Fig. 16 Tool wear under different cutting environments

$$R_a = 2.335 - 0.00666V_c + 0.00072S_o + 0.040365t - 0.000294V_c^2 + 0.000208S_o^2 + 0.045t^2 - 0.000285V_cS_o + 0.001111S_ot + 0.0057V_ct \quad (1)$$

$$P_z = 90.34 - 1.9508V_c + 1.79458S_o + 67.868t - 0.0171V_c^2 + 0.0151S_o^2 - 12.00t^2 - 0.0015V_cS_o + 0.0634S_ot - 0.7543V_ct \quad (2)$$

For the purpose of modeling, 48 combinations of surface roughness and cutting force were taken only from the machining of 42CrMo4 steel with nano fluid. Then the values of dependent variables (surface roughness, Ra and cutting force, Pz) and independent variables (cutting speed, Vc; feed rate, So; depth of cut, t) are incorporated into the RSM model in Minitab 16.0. The values of the regression coefficients for surface roughness and cutting force are in Table 10.

As the models residuals approximately draw straight lines as shown in Fig. 17, it indicates that both equations fit well with incorporated data. Also the higher values of regression coefficient proves the good predictability of

Table 9 Values of flank wear after various machining time

Machining time (s)	Flank wear in dry condition	Flank Wear with conventional cutting fluid (μm)	Flank wear with nanofluid (0.3 vol% CNT)	Percentage reduction in flank wear	
				Milling with conventional cutting fluid	Milling with nanofluid
30	95	84	64	12	33
60	109	96	74	12	32
90	129	111	89	14	31
120	146	127	99	13	32
180	178	154	123	13	31
240	201	178	135	11	33
300	254	227	165	11	35
432	289	253	189	12	35
540	342	290	210	15	39

Table 10 Regression coefficients of RSM regression models

Models	R-square (%)	R-square (adjusted) (%)	R-square (predicted) (%)
R_a	98.58	98.25	97.56
F_z	99.70	99.63	99.49

the generated equations. Finally, the performance of two equations was evaluated by both absolute percentage error (APE) as shown in Eq. (3) and model predictive error (MPE) as shown in Eq. (4).

$$APE = \left(\frac{|Actual - Predicted|}{Actual} \right) \times 100 \quad (3)$$

$$MPE = \frac{1}{N} \sum_{n=1}^{N} \left(\frac{|Actual - Predicted|}{Actual} \right) \times 100 \quad (4)$$

The results of the prediction of surface roughness and cutting force by RSM are shown in Table 11. In modeling of surface roughness and cutting force, the model predictive error was found to be 0.71% and 0.66% respectively. Based on the lower MPE, it can be said that these two generated

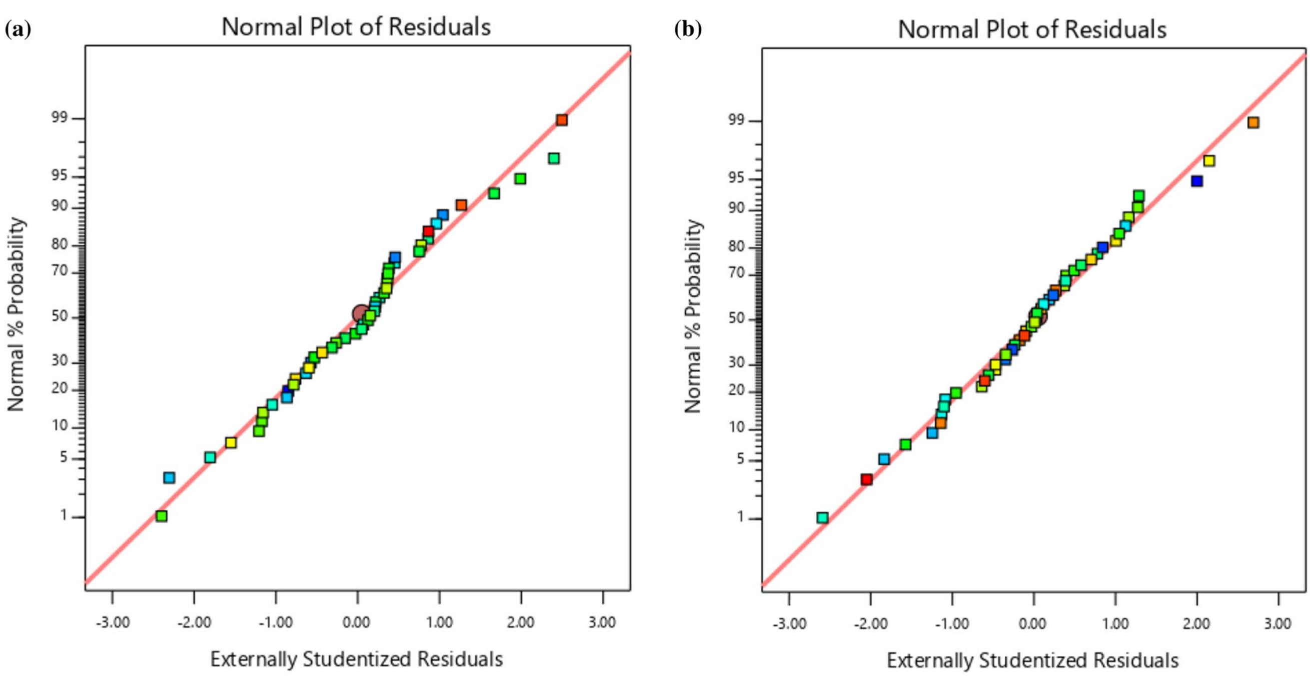


Fig. 17 Normal probability plot for **a** surface roughness and **b** cutting force

Table 11 Performance of RSM models

Predicted surface roughness, Ra (µm)			Predicted cutting force, Pz (N)		
Experimental	RSM	RSM-APE (%)	Experimental	RSM	RSM-APE (%)
2.58	2.59	0.52	211	211.32	0.15
2.52	2.50	0.59	202	202.18	0.09
2.45	2.44	0.29	195	195.93	0.47
2.34	2.31	1.19	185	182.99	1.08
2.68	2.66	0.88	221	222.15	0.52
2.56	2.57	0.47	213	212.46	0.26
2.52	2.51	0.27	206	205.82	0.09
2.39	2.38	0.09	196	192.13	1.97
2.74	2.72	0.56	228	231.49	1.53
2.69	2.64	1.68	221	221.23	0.10
2.58	2.59	0.33	212	214.21	1.043
2.43	2.47	1.60	201	199.77	0.61
MAPE		0.71			0.66

equations can be used to predict surface roughness and cutting force.

8 Conclusions

- Sedimentation and zeta potential analysis confirmed that the sample made of less than 0.4 Vol% CNTs shows higher stability than any other sample. Also, it is found that ultrasonication time of 1.30 h with 1 h magnetic stirring and presence of 0.6 vol% sodium dodecyl sulfate as surfactant is optimum to prepare a stable nanofluid with 0.3 vol% cnts.
- Thermal conductivity increases with the increase in concentration of CNTs and temperature. The highest value of thermal conductivity was 1.54 which was 35% greater than thermal conductivity of conventional cutting fluid.
- The viscosity of nano fluid samples exhibited a specific trend i.e. the viscosity was increased with the addition of CNT particles. As the viscosity of all nano fluid samples is similar to water, it can be claimed as a good cutting fluid.
- Conventional cutting fluid showed lower thermal conductivity and higher viscosity than all nano fluid samples. Therefore, it can be said that the nano fluid had better properties to be better cutting fluid than conventional cutting fluid.
- Application of CNT based nano fluid resulting in maximum 34% lesser surface roughness and 29% lesser cutting temperature than machining without any fluid is evidence of effectiveness of CNTs in machining, whereas conventional cutting fluid resulted in maximum 16% and 22% lesser surface roughness and cutting temperature respectively.
- Also the values of cutting force and tool wear has shown a significant reduction of 33% and 39% respectively while using nanofluid compared to dry milling.
- Finally, it can be concluded that the sample made of 0.3 vol% CNTs has a great potential to be used as an efficient coolant and lubricant in machining owing to its higher stability, greater thermal conductivity and lower viscosity.
- The explained internal cooling system for delivering nano fluid while end milling hardened material have been proved to be an effective method to reduce cutting temperature, surface roughness, cutting force and tool wear.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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