Effect of nanoparticles on the performance of magnetorheological fluid damper during hard turning process

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Abstract: Magnetorheological (MR) fluid damper which allows the damping characteristics of the damper to be continuously controlled by varying the magnetic field is extensively used in metal cutting to suppress tool vibration. Even though magnetorhelogical fluids have been successful in reducing tool vibration, durability of magnetorhelogical fluids remains a major challenge in engineering sector. Temperature effect on the performance of magnetorhelogical fluids over a prolonged period of time is a major concern. In this paper, an attempt was made to reduce temperature and to improve viscosity of magnetorhelogical fluids by infusing nanoparticles along with MR fluids. Aluminium oxide and titanium oxide nanoparticles of 0.1% and 0.2% concentration by weight were considered and experimental tests were conducted to study the influence of nanoparticles on the performance of magnetorheological fluid. From the experimental results it was observed that the presence of nanoparticles in MR fluid reduces temperature and increases the viscosity of MR fluid thereby increasing the cutting performance during turning of hardened AISI 4340 steel.

Keywords: magnetorheological (MR) fluid; nanoparticles; tool vibration; hard turning; temperature; viscosity.

1 Introduction

Machining is a complicated process in which many variables directly affect the desired results. Among them, tool vibration is the most critical phenomenon which affects the life of the cutting tool, quality of the components machined and functional behavior of the machined tools. Tool vibration is a dynamic instability of cutting process, which is a result of interaction between metal cutting process and the dynamics of machine tool. The presence of such vibrations leads to poor surface finish, increase in tool wear, cutting tool damage and production of infuriating noise [1]. In order to suppress tool vibration and to improve cutting performance, many types of dampers have been used in the past [2, 3]. Among the different dampers, magnetorheological fluid damper was found to be more effective than the conventional viscous damper [4]. Magnetorheological (MR) fluid was first reported by Rabinow [5] in 1948 and he concluded that MR fluids are magnetic field-controllable fluid whose rheological behavior depends on the strength of the magnetic field. When exposed to an external magnetic field, this fluid instantaneously changes from a viscous fluid to a semisolid and forms a chain-like structures, depending on the directions of the field, with a controllable yield strength. Carlson and Sproston [6] investigated the properties and applications of commercially available MR fluids and it was observed that the MR fluids can operate at temperatures from −40 to 150 °C, with only slight variation in yield stress. Lord Corporation [7] developed MR fluid shock absorbers for automobiles and they concluded that such shock absorbers respond instantly and can control varying levels of vibration, shock and motions. Genc

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and Phule [8] observed that by varying the parameters associated with MR fluids like volume, particle size and fraction of solids, the properties of the MR fluids can be varied.

Wang and and Meng [9] applied MR damper in a cantilever rotor system to increase its stability. Yang et al. [10] studied the dynamic performance of MR dampers and found that MR damper provides large controllable damping force and a parallel connection of the damper coils results in a faster response time than a series connection. Choi et al. [11] analyzed the viscosity of the MR fluids using a rotational rheometer equipped with a magnetic field supplier and they found that this magnetic-composite-particle based MR fluid exhibited typical MR characteristics. Wereley et al. [12] used a mixture of conventional micron-sized particles and nano-meter sized particles in MR suspension and they observed that the settling rate of such bidisperse fluids using nanometer-sized particles is reduced because the nanoparticles fill pores created between the larger particles, thereby reducing fluid transport and increasing yield stress. Spelta et al. [13] studied the control of magnetorheological dampers for vibration reduction in a washing machine. Song et al. [14] observed that MR fluids with magnetic carbonyl iron (CI) nanoparticles demonstrated slightly higher yield, suggesting that pure CI and CI nanoparticle additive were being oriented in the magnetic field direction under an applied magnetic field and with much strengthened structure. Park et al. [15] examined the characteristics of MR fluid which was prepared by suspending the composite particles in mineral oil, using a rotational rheometer in a parallel plate with a magnetic field supplier. They concluded that the properties of composite based MR fluid exhibit typical MR behaviour with maximum yield stress of 800 Pa when 343 kA/m of magnetic field was applied. Avinash et al. [16] studied the damping characteristics of air, silicon oil and magneto rheological fluid on twin tube damper and found that damping rate of MR fluid has much better damping characteristics compared to the silicon oil and air. Sam Paul et al. [17] used magnetorheological damper to reduce tool vibration during hard turning with minimal fluid application and they also considered parameters like shape of the plunger, viscosity of the oil, size of the particle and type of current

to optimize magnetorheological fluid parameters [18].

As mentioned before, magnetorheological fluid damper is predominantly used in applications where vibration control or transfer of force is required. Even though magnetorheological fluid have made considerable progress, there are no systematic published studies on the factors affecting the stability of magnetorheological fluid. In magnetorheological fluids, factors like rise in temperature over extended periods of time are some of the mentioned factors. Fluids subjected to thickening after prolonged use and settling of ferro-particles are the factors of greater concern as they affect the performance of the fluid being employed. Unfortunately methods to overcome these difficulties have not been fully covered in literatures. Continuous operations of magnetic coils produce heat which causes an increase in temperature of the MR fluids as well on the damped body. Viscosity and volume of a fluid is closely related to the temperature and in the case of MR fluids, the viscosity decreases due to rise in temperature. This decrease in viscosity reduces post yield damping [19]. Shah et al. [20] observed that sedimentation is the most important issue in the stabilization of magnetorheological damper which also affects the performance of MR damper. Carbonyl iron was used as magnetisable particles for MR fluids due to its high magnetic permeability, soft magnetic characteristics and from the results it was observed that CI based MR fluids have an issue with sedimentation of suspended particles due to density mismatch to the MR fluids [14].

The main focus of this investigation is to study the effect of nanoparticles impregnated with magnetorheological fluid on the stability of MR fluids and performance indices of machine tools like tool vibration, surface roughness, cutting force and cutting temperature. When an electric field is applied to the MR fluids, the fluid becomes a semisolid and behaves as a viscoelastic spring with non-linear vibration characteristics. This transition is reversible and can be achieved in a few milliseconds. Nanoparticles like titanium oxide and aluminium oxide were added to the MR fluids and cutting experiments were conducted to arrive at a set of parameters that can reduce tool vibration and hence promote better cutting performance during turning of AISI 4340 steel of 46 HRC using

hard metal insert with sculptured rake face. The above mentioned studies reveal that the use of magnetorheological damper was found to be effective if it is applied in a defined way.

2   Selection of tool and work material

Multicoated hard metal inserts with sculptured rake face geometry with the specification SNMG 120408 MT TT5100 from Taegu Tec were used in the present study. The tool holder used is hardened steel having the specification PSBNR 2525 M12. This selection was done based on the information available in the Ref. [21]. The work piece material was an AISI 4340 steel which was hardened to 46 HRC by heat treatment. It is a general-purpose steel having a wide range of application in automobile and allied industries by virtue of its good hardenability enabling it to be used in fairly large sections. Bars of 80 mm diameter and 360 mm length were used in the present investigation. The Chemical composition in weight % of AISI 4340 Steel are 0.41% C, 0.87% Mn, 0.28% Si, 1.83% Ni, 0.72% Cr, 0.20% Mo and rest Fe [22].

3   Development of magnetorheological damper

Magnetorheological fluids belong to a class of controllable fluids which has the ability to reversibly change from a free-flowing, linear, viscous liquid to a semi-solid with considerable yield strength in milliseconds when exposed to a magnetic field. When exposed to a magnetic field, the suspended particles in the fluid polarize and interact to form a structure that aligns with the magnetic field resisting the shear deformation. This change in the material appears as a dramatic increase in apparent viscosity and the fluid develops the characteristics of a semi-solid state. The apparent viscosity and shearing stress can be controlled by changing the intensity of magnetic field [23]. The viscosity of MR fluid increases as the strength of the magnetic field increases, and even it can behave as semi-solid. When the applied magnetic field vanishes, the MR fluid reverts to its previous, fluid state. The transformation between the liquid to the semi solid phase takes place instantly [24].

A line sketch of the MR damper developed and used for this investigation is shown in Fig. 1. It consists of a plunger (P) made of stainless steel 410 which can move inside a cup made of stainless steel 410 containing MR fluid, which may be magnetized by passing current through the coil. Threads were cut at the end of the plunger that matched with the threads cut on a hole of the tool holder so that the plunger can be held rigidly with the tool holder as shown in Fig. 1. The coil consists of 800 turns of copper wire of 28 gauge [18]. Figure 2 presents dissembled view of the MR fluid damper and photograph representing the location of the MR fluid damper attached to the tool holder is shown in Fig. 3.

When the coil is energized, MR fluid is activated and offers resistance to the motion of the plunger, thereby damping the tool vibration. The damping action of the MR fluid damper depends on the following factors (i) the shape (S) of the plunger, (ii) the viscosity index (p) of the fluid medium, and (iii) size (m) of the ferro magnetic particles [18]. The magnetorhoelogical fluid
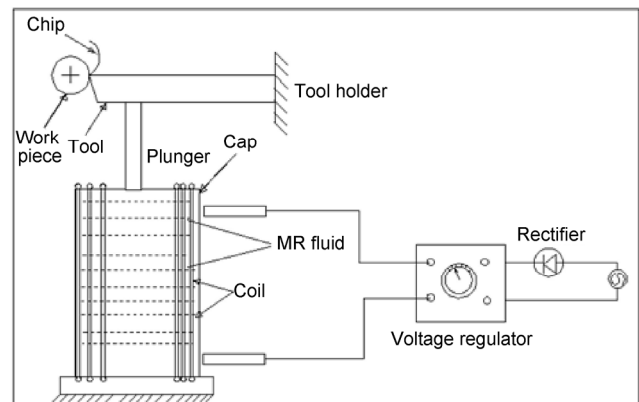

Fig. 1   Line sketch of MR fluid damper.
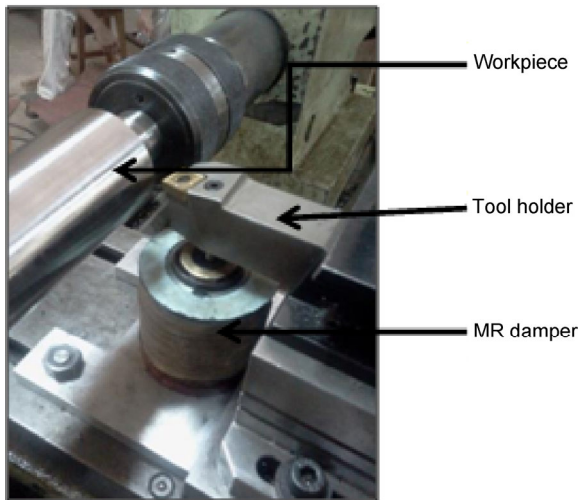

Fig. 2   Dissembled view of the MR damper.

Fig. 3 Photograph of the experimental setup with MR fluid damper.

parameters used in this study is shown in Table 1 and these values are taken based on preliminary experiment and based on the information available in the Ref. [18].

3.1 Effect of nanoparticles on viscosity

In order to reduce the temperature induced and to avoid sedimentation in magnetorheological fluid damper when exposed to magnetic field, it was momentous to use additives along with magnetorheological fluid. Among the different additives available, nanoparticles have considerable influence on sedimentation and stability. In this paper aluminium oxide and titanium oxide nanoparticles were identified based on the fact that titanium oxide has the property to enhance iron powder's magnetic property and aluminium oxide has the tendency to get absorbed in iron-oil interface and also avoids the aggregation between the iron particles

Table 1 Parameters of magnetorheological fluid.

MR fluid parameters	Specification
Size of the ferromagnetic particles	75 microns
Composition of the MR fluid	70:30 (70% ferromagnetic particles and 30% oil by weight)
Viscosity of the oil	SAE 40
Type of plunger	Conical
Current	DC current of 30 voltage
Coil winding	Wound a direction parallel to the axis of the MR damper (vertical winding)

induced by its magnetization. In addition, aluminium oxide possesses the property of high hardness, high insulation, good dimensional stability and has the tendency to significantly improve smoothness, thermal fatigue resistance, fracture toughness, creep resistance and wear resistance [25]. Aluminium oxides rank amongst the less toxic substances and only exhibit toxic effects in high concentrations. Also by using aluminium oxide, phase stability will increase which is one of the most vital requirement in magnetorheological damper. Another nanoparticle titanium oxide is thermally stable, non-flammable and not classified as hazardous according to the United Nations (UN)' Globally Harmonized System of Classification and Labeling of Chemicals (GHS) and also has chemical stability, non-allergic, non-irritant and ultra violet protective properties. Titanium oxide when impregnated with magnetorheological fluid, has the influence to be fused together by chemical bonds to form aggregates [26]. These aggregates further agglomerate via van der Waals attractive forces to form particles which provide better damping force. In addition, both nanoparticles are easily affordable, economically viable and less toxic.

In this investigation aluminium oxide and titanium oxide nanoparticles of an average size of 98.60 nm and 20.35 nm were infused with MR fluids. The SEM images of TiO_2 and Al_2O_3 nanoparticles are shown in Fig. 4. In this study, 0.1% (0.17 gms), 0.2% (0.34 gms) of TiO_2 and 0.1% (0.16 gms), 0.2% (0.32 gms) of Al_2O_3 were added to the magnetorheological fluid composition. The viscosity of MR fluids with and without nanoparticles in different volume concentrations were measured using Brookfield's Viscometer (LVDV-E model) at 60 rpm and 100 rpm spindle speed. The temperatures of MR fluids inside the damper with and without nanoparticles when subjected to magnetic field were measured using k type thermocouple. The experimental value of viscosity and temperature for MR fluid with and without nanoparticles is presented in Table 2 and Fig. 5.

From the results it was observed that titanium oxide of 0.2% concentration when impregnated with MR fluid provides better viscosity and reduces the temperature in MR fluids when compared to other nanoparticles. In order to validate further, MR fluid with nanoparticles were tested in machining conditions.
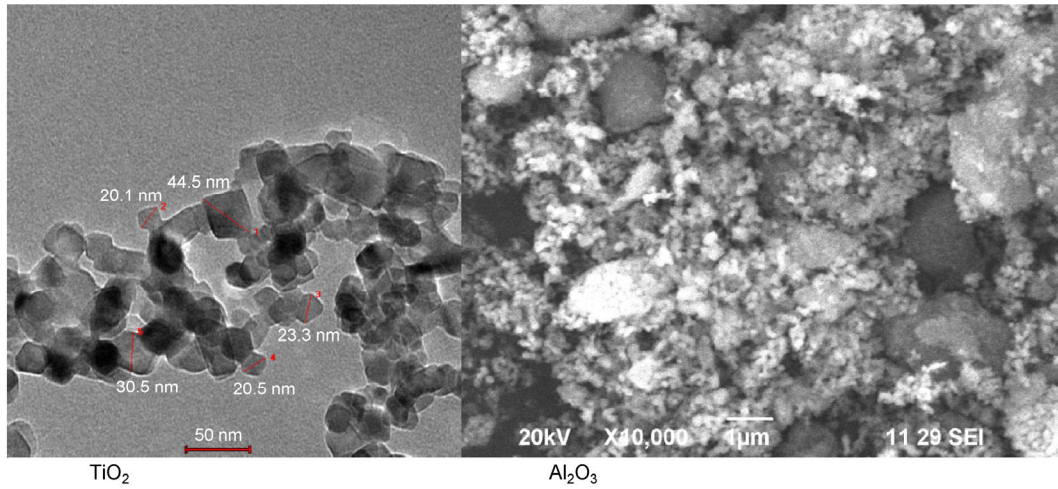
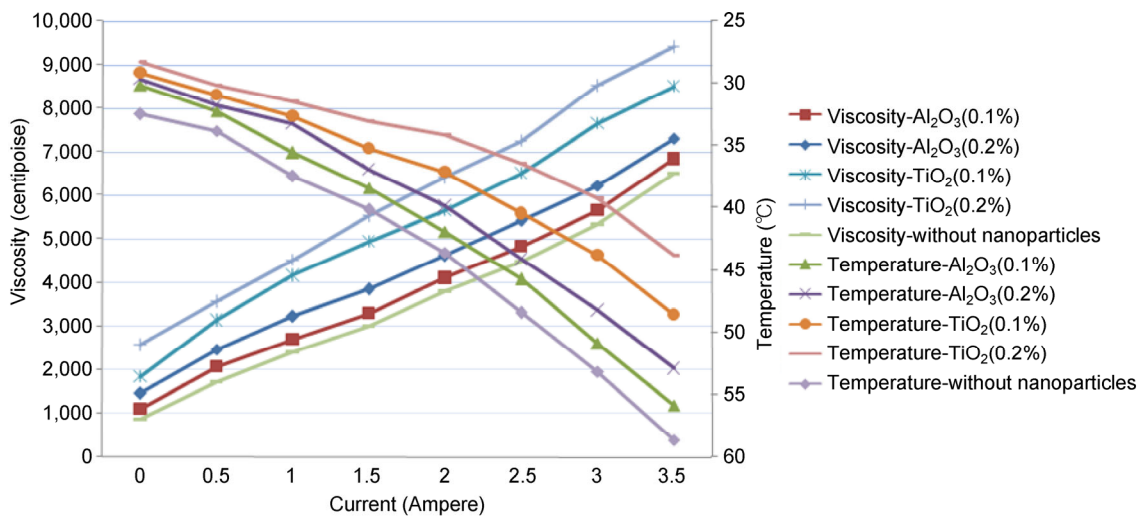**Fig. 4** SEM images of TiO$_2$ and Al$_2$O$_3$ nanoparticles.

Fig. 5 Viscosity and Temperature values of MR fluids with and without nanoparticles.

Table 2 Viscosity and temperature of MR fluids with and without nanoparticles.

Current (A)	Viscosity of magnetorheological fluid damper with nanoparticles (m^2/s)				Temperature of magnetorheological fluid damper with nanoparticles (°C)				Viscosity of MR fluid without nano-particles (m^2/s)	Temperature of MR fluid without nano-particles (°C)
	Al$_2$O$_3$ (0.1%)	Al$_2$O$_3$ (0.2%)	TiO$_2$ (0.1%)	TiO$_2$ (0.2%)	Al$_2$O$_3$ (0.1%)	Al$_2$O$_3$ (0.2%)	TiO$_2$ (0.1%)	TiO$_2$ (0.2%)		
0	1100	1454	1842	2567	30.11	29.64	29.11	28.24	880	32.47
0.5	2063	2470	3140	3567	32.23	31.74	30.91	30.12	1720	33.79
1	2697	3220	4163	4520	35.54	33.24	32.64	31.4	2404	37.46
1.5	3301	3853	4957	5530	38.42	36.89	35.21	32.98	3001	40.13
2	4111	4623	5667	6412	41.88	39.83	37.12	34.12	3800	43.58
2.5	4843	5427	6523	7254	45.74	44.12	40.45	36.45	4500	48.4
3	5657	6239	7658	8520	50.86	48.23	43.81	39.23	5345	53.17
3.5	6839	7308	8518	9410	55.84	52.92	48.54	43.84	6500	58.61

4 Experimental setup

Cutting experiments were carried out on a Kirloskar Turn Master-35 lathe. A 12 run experiment was designed based on Taguchi technique in which the input variables namely the magnitude of current and nanoparticle composition were varied at different levels. Experiments were conducted with two replications and each experiment lasted for 120 seconds and also the experimental work was carried out in dry turning. The cutting velocity was kept at 100 m/min, the feed at 0.12 mm/rev, depth of cut at 1.2 mm, a DC current of 30 voltage, conical plunger and 75 micron size particles with SAE 40 oil was used in this investigation and the design matrix is presented in Table 3. These data were taken based on the information available in the Ref. [18]. The main cutting force, average surface roughness and the amplitude of tool vibration were measured during each experiment. The main cutting force was measured using a Kistler tool force dynamometer and average surface roughness R_a was measured using Mahr TR100 surface roughness tester of type MarSurf GD 25. Amplitude of tool vibration was measured using a piezoelectric-type vibrometer where the pickup of the vibrometer was mounted at the top of the tool holder near to tool tip. Since the vibration, particularly in the radial direction, is known to have a deleterious effect on the machined surface texture [27], the amplitude of tool vibration in vertical direction was measured in this study.

5 Results and discussion

The main cutting force, cutting temperature, average surface roughness and the amplitude of tool vibration measured during each experiment are presented in Table 3.

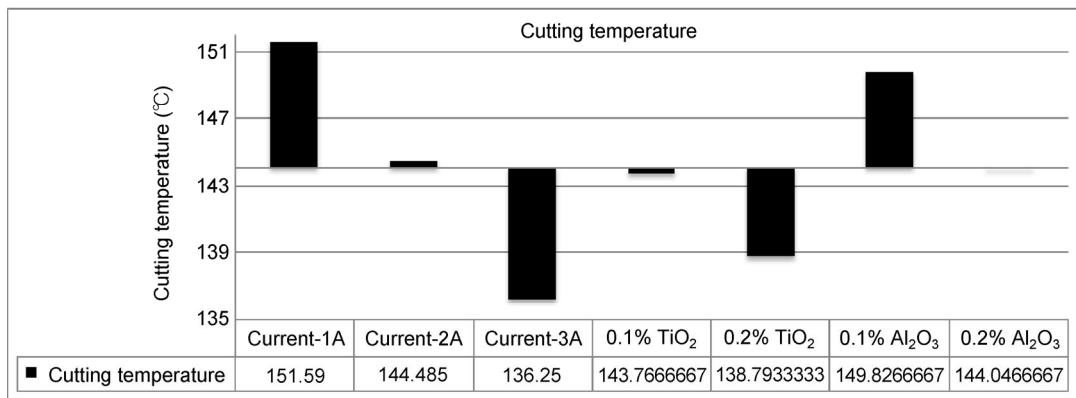The relative significance of input parameters on the cutting force is shown in Fig. 6 and Fig. 7 presents the relative significance of the input parameters on cutting temperature. The relative significance of input parameter on surface roughness and tool vibration are shown in Figs. 8 and 9 respectively.

The experimental results were analyzed using Qualitek-4 and the levels of input parameters for achieving minimum tool vibration, cutting force, cutting temperature and surface roughness are presented in Table 4.

From Table 4, it is observed that for minimizing tool vibration and for achieving better cutting performance, direct current of magnitude 3A should be used along with a cone shaped plunger having particle size of 75 microns mixed with oil of viscosity index SAE40 impregnated with nanoparticles of 0.2% TiO_2.

In direct current, as there is no fluctuation in the magnetic field, more stable orientation of magnetic particles will occur which enhances the damping capability of damper. Current applied at high level (3 A) can offer better damping capability as the strength of the magnetic field depends on the applied current. Higher the current supplied, higher will be the strength

Table 3 Summary of experimental results.

Run	Current (A)	Nanoparticles	Cutting force (N)	Cutting temperature (^oC)	Amplitude of tool vibration (mm)	Surface roughness R_a (μm)
1	1	0.1% TiO_2	60.42	151.45	0.36625	1.0734
2	1	0.2% TiO_2	58.75	146.89	0.28535	1.0331
3	1	0.1% Al_2O_3	65.61	157.24	0.70481	1.2564
4	1	0.2% Al_2O_3	62.73	150.78	0.53815	1.2012
5	2	0.1% TiO_2	55.87	145.08	0.25790	0.9586
6	2	0.2% TiO_2	52.39	139.23	0.20014	0.8903
7	2	0.1% Al_2O_3	60.89	149.71	0.62444	1.1166
8	2	0.2% Al_2O_3	58.78	143.92	0.39310	1.0165
9	3	0.1% TiO_2	48.56	134.77	0.18181	0.8366
10	3	0.2% TiO_2	45.04	130.26	0.12531	0.7283
11	3	0.1% Al_2O_3	54.25	142.53	0.38733	0.9781
12	3	0.2% Al_2O_3	51.91	137.44	0.27176	0.9075
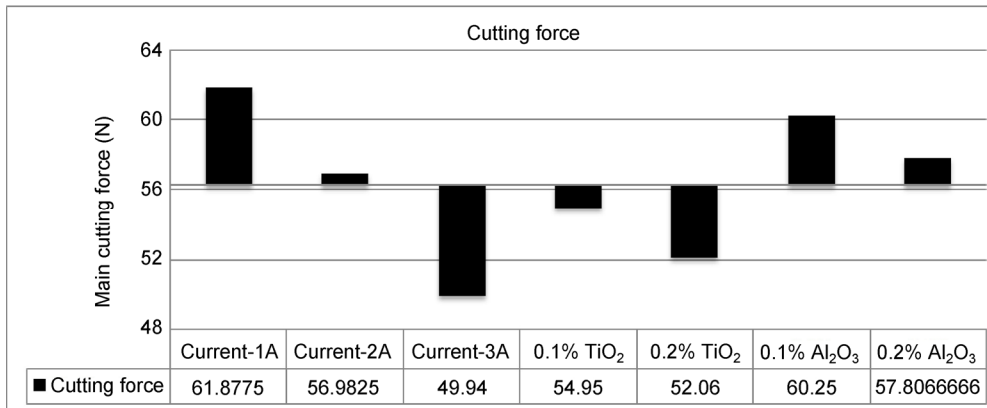
Fig. 6   Relative significance of input parameters on cutting force.

	Current-1A	Current-2A	Current-3A	0.1% TiO$_2$	0.2% TiO$_2$	0.1% Al$_2$O$_3$	0.2% Al$_2$O$_3$
■ Cutting force	61.8775	56.9825	49.94	54.95	52.06	60.25	57.8066666

Fig. 7   Relative significance of input parameters on cutting temperature.

	Current-1A	Current-2A	Current-3A	0.1% TiO$_2$	0.2% TiO$_2$	0.1% Al$_2$O$_3$	0.2% Al$_2$O$_3$
■ Cutting temperature	151.59	144.485	136.25	143.7666667	138.7933333	149.8266667	144.0466667
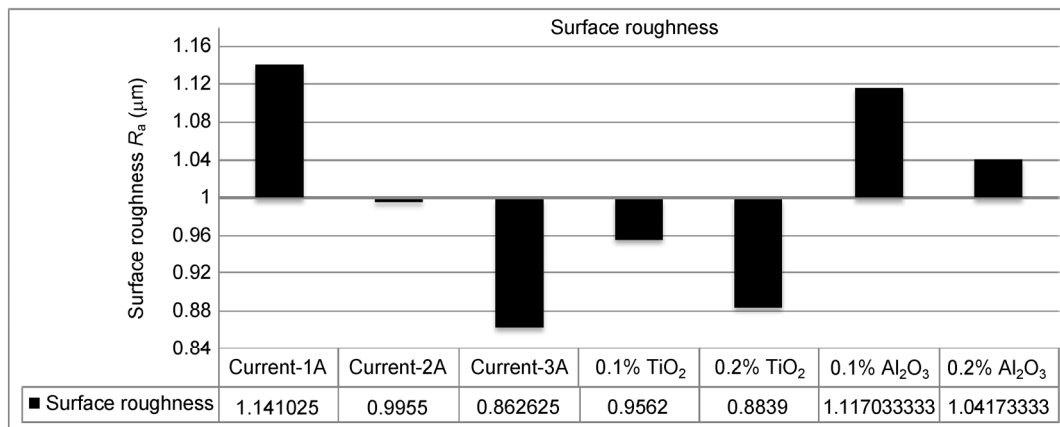
Fig. 8   Relative significance of input parameters on surface roughness.

	Current-1A	Current-2A	Current-3A	0.1% TiO$_2$	0.2% TiO$_2$	0.1% Al$_2$O$_3$	0.2% Al$_2$O$_3$
■ Surface roughness	1.141025	0.9955	0.862625	0.9562	0.8839	1.117033333	1.04173333

of the magnetic field and better will be the damping ability. But in magnetorheological damper when a current of very high magnitude (more than 3 A) was applied, MR fluid will lose its damping capability due to the formation of high temperature. When the supply of current was low, the tendency to form semi solid reduces which reduces the damping ability of

magnetorheological fluids. Figure 5 show the curves of temperature and viscosity for different current magnitude. From this it appears that, when a current of 0.5 A was applied to the magnetorheological fluid without nanoparticles, temperature and viscosity was found to be 33.79 °C and 1,720 whereas it was 58.61 °C and 6,500 for the current of 3.5 A. At the
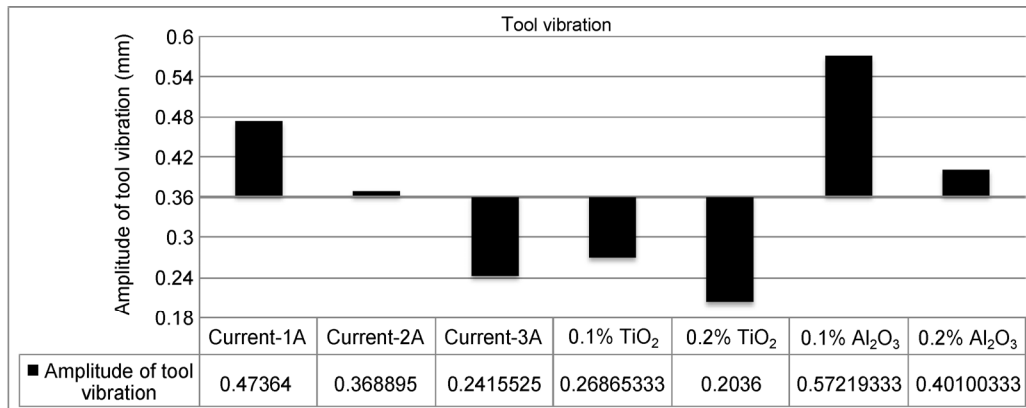
Fig. 9 Relative significance of input parameters on the amplitude of tool vibration.

Table 4 Levels of input parameters for getting optimum performance.

Expected outcome	Current (A)	Nanoparticle composition
To minimize cutting force	3	0.2% TiO_2
To minimize cutting temperature	3	0.2% TiO_2
To minimize tool vibration	3	0.2% TiO_2
To minimize surface roughness	3	0.2% TiO_2

same time, when nanoparticles either Al_2O_3 or TiO_2 are added to MR fluids, temperature decreases and viscosity increases considerably. When supply current increases, the viscosity of the MR fluid increases, leading to increase in the damping ability of MR fluid. Moreover increase in current magnitude results in high temperatures and can lead to safety problems. From Figs. 6–9 it appears that cutting performance like cutting temperature, tool vibration, cutting force and surface finish was found to be better when a current of 3 A was applied.

One of the most effective ways to improve the strength and viscosity of magnetorheological damper is to use nanoparticles along with iron particles to the base fluid. In this study two different nanoparticles Al_2O_3 and TiO_2 having 0.1% and 0.2% weight were considered separately. From the results shown in Table 4, it was observed that the presence of MR damper having titanium oxide nanoparticles of 0.2% volume concentration provides better cutting performance when compared to other nanoparticles. Nanoparticles fill the minute opening created between larger particles and reduce the fluid movement during creeping flow. This also leads to the reduction in settling rate of MR

fluid which in turn helps in improving the viscosity of MR fluids. Moreover, as the nanoparticles in MR fluids scatter themselves by thermal convection; temperature of MR fluids was controlled effectively for an increase in magnetic field. Al_2O_3 which does not melt easily, when used along with MR fluids enhances the damping capability of damper and offers better cutting performance through reduction in cutting temperature. However, TiO_2 possesses a coefficient of expansion which is one third the value of Al_2O_3 assist in better way to reduce temperature and increase viscosity of MR fluids during machining. Even though homogeneous distribution of alumina particles size and pores size incorporated between the matrix particles results in lowering the flaw size, titanium dioxide particles have conductivity which will increase with increase in temperature and are strongly bound together by chemical bonds to form aggregates. These aggregates further agglomerate by Vander Waals attractive forces to form particles in good strength.

Cutting experiments were conducted with the input parameters kept at levels as indicated in Table 4 and the performance was compared with the cutting performance during dry turning for magnetorheological damper with and without nanoparticles and also with tool holder without damper.

A comparison of the cutting performance for the three cases is shown in Table 5 and it can be seen that the MR fluid damper impregnated with nanoparticles can suppress tool vibration, reduce cutting temperature, cutting force and improve surface finish effectively when compared to magnetorhelogical damper without nanoparticles.

Table 5 Comparison of performance for MR damper with and without nano particles.

Parameters	Damper with nanoparticles	Damper without nanoparticles	Without damper
Amplitude of tool vibration (mm)	0.134	0.151	0.226
Surface roughness R_a (μm)	0.741	0.852	1.202
Main cutting force (N)	44.78	48.27	60.82
Cutting temperature (^{o}C)	130.43	143.84	184.74

6 Conclusion

In this study, an attempt is made to investigate the effect of nanoparticles when impregnated with magnetorheological fluid on cutting temperature, cutting force, surface roughness and tool vibration during hard turning of AISI 4340 steel using hard metal inserts with sculptured rake face. A magnetorheological fluid system has been developed, two different nanoparticles Al_2O_3 and TiO_2 having 0.1% and 0.2% weight were considered separately and series of experiments have been carried out which lead to the following conclusions:

1. A magnetorheological fluid damper when impregnated with nanoparticles can provide better stability, higher viscosity and better cutting performance during hard process.

2. For achieving better damping capability and cutting performance, the damper is to be made with MR fluids impregnated with titanium oxide Ferro and magnetized with direct current of higher magnitude.

3. Nanoparticles used along with MR fluids reduce cutting temperature in the MR fluid, outside the core and during machining process.

Acknowledgements

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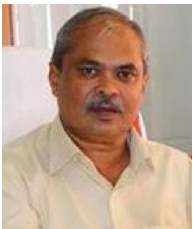
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