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Effect of magnetorheological fluid on tool wear during hard turning with minimal fluid application

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ABSTRACT

Tool wear is a very complex phenomenon which can lead to machine down time, product rejects and can also cause problems to personnel. The present investigation aims at developing a magnetorheological fluid setup that can be attached to the tool holder for reducing tool wear during hard turning with minimal fluid application. The magnetorheological fluid acts as a viscoelastic spring with non-linear vibration characteristics that are controlled by parameters like the viscosity index of the fluid medium, shape of the plunger, current through the coil and size of the ferromagnetic particles. Cutting experiments were conducted to arrive at a set of magnetorheological fluid parameters that can offer better damping characteristics to minimize tool wear and promoting better cutting performance during turning of AISI 4340 steel of 46 HRC with minimal fluid application using hard metal insert with sculptured rake face. From the results, it was observed that the presence of magnetorheological fluid setup during hard turning with minimal fluid application attached to the tool holder reduces tool wear and brought forth better cutting performance. Commercialization of this idea is sure to benefit the metal cutting industry.

1. Introduction

Conventionally when cylindrical parts requiring high hardness as functional requirement are to be machined, the work piece is turned to the near net shape, hardened to the required hardness and ground to the final dimension. This lengthy process cycle can be avoided by hard turning which is intended to replace or limit traditional grinding operations [1]. But hard turning involves very large quantities of cutting fluid. Procurement, storage and disposal of cutting fluid involve expenses and it has to comply with environmental legislation such as OSHA as well. Pure dry turning is a solution to this problem as it does not require cutting fluid at all. But pure dry turning requires Ultra Hard cutting tools and extremely rigid machine tools and it is difficult to implement in the existing

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shop floor as the machine tools may not be rigid enough to support hard turning. In this context, turning with minimal fluid application is a feasible alternative where in, extremely small quantities of cutting fluid with high velocity are applied at the critical contact zones, in the form of a pulsing slug so that for all practical purposes it resembles pure dry turning and at the same time, free from all the problems related to large scale use of cutting fluid as in conventional wet turning.

During minimal fluid application, extremely small quantities (about 2 ml/min) of cutting fluids are applied at critical zones in the form of a high velocity pulsed jet so that fluid particles reach the tool chip interface and provide enhanced rake face lubrication. Varadarajan et al. [2] observed that during minimal fluid application, the overall cutting performance was superior to that during dry turning and conventional wet turning.

In hard turning with minimal fluid application, tool wear becomes an important parameter affecting surface roughness of finished parts [3]. Tool wear is a very complex phenomenon which can lead to machine down time, product rejects and can also cause problems to personnel. The life of a tool can come to an end in two major ways. The first one is the progressive tool wear as a result of the wearing away of certain regions of the face and flank of the cutting tool. This leads to the gradual deviation of the surface finish from the tolerance limit as the tool wear progresses and finally necessitates the replacement of the cutting tool. The second mode is the catastrophic tool failure bringing the life of the tool to a premature end. The present study addresses the progressive type of tool wear. In metal cutting, progressive tool wear occurs in three main forms namely adhesion wear, abrasion wear and diffusion wear. Each wear form has its own characteristic symptoms. Variation of cutting force can carry information on adhesive and breakage type of tool wear. Excessive tool vibration is an index of abrasive type of tool wear and it will increase the tool wear and cause poor surface finish during machining [4]. Diffusion and crater type of tool wear are accompanied by excessive cutting temperature and the rate of diffusion increases exponentially with increase in temperature. High cutting force, excessive cutting temperature and increase in tool vibration are indications of progressive tool wear [5].

In actual cutting conditions, the vibration of the cutting tool depends on the tool wear and increases as the tool wear progresses [6]. The tool will be sharp in the beginning and slowly loses its sharpness as the cutting process progresses. Hence the amplitude of tool vibration will be less during the initial stage which increases slowly as the tool wear progresses and becomes very high when the tool is nearing the end of its life. Hence comparatively less damping is needed in the beginning and more damping capability is desirable when the tool is nearing the end of its life. Hence for a comprehensive control of surface finish, a damper in which the damping capability can be varied in line with the magnitude of tool wear will be more desirable than a damper with a fixed damping capability. In such a system, the damping capability will be varied by adjusting some controlling parameters of the damper as needed by the magnitude of the tool wear.

Spencer et al. [7] was the first among the scientists who tested magnetorheological fluid dampers to improve cutting performance during machining. J.D. Carlson and J.L. Sproston [8] investigated the properties and applications of commercially available magnetorheological fluids and it was observed that the magnetorheological fluids can operate at temperatures from −40 to 150 °C, with only slight variation in the yield stress. Also this rheological fluid damper was found to be more effective than the conventional viscous damper [9]. Wang and Fei [10] tried to suppress chatter in boring bar using an electro rheological fluid damper and developed an on line chatter detection and control system. Lord Corporation [11] developed magnetorheological fluid shock absorbers for automobiles and it was observed that such shock absorbers can respond instantly and can control varying levels of vibration, shock and motions. Genc and Phule [12] observed that the properties of the magnetorheological fluids can be varied by varying the parameters associated with magnetorheological fluids like volume, particle size fraction of solids, etc. Also it was reported that using MR fluid dampers, chatter could be suppressed more effectively by adjusting the damping and natural frequency of the system in boring bar [13]. Sathianarayanan et al. [14] investigated the suppression of chatter in boring tools using MR damper and observed that MR damper reduces the possibility of chatter and improves the stability of boring operation.

In the present investigation, an attempt was made to develop a magnetorheological fluid system which can be easily attached to the tool holder for reducing tool wear and improving cutting performance during hard turning with minimal fluid application. When an electric field is applied to the magnetorheological fluid, it becomes a semisolid and behaves as a viscoelastic spring with non-linear vibration characteristics. This transition is reversible and takes place in a few milliseconds. Cutting experiments were conducted to arrive at the optimum viscosity of the fluid, shape of the plunger and the magnitude of the current passing through the magnetizing coil that can offer a damping characteristics which will minimize tool wear and promote better cutting performance during turning of AISI 4340 steel of 46 HRC with minimal fluid application using hard metal insert with sculptured rake face. It was observed that the presence of magnetorheological fluid system attached to the tool holder reduces tool wear and improves cutting performance. The scheme which is specifically developed for hard turning with minimal fluid application may be extended to improve cutting performance during normal turning operations as well.

2. Selection of work material

AISI 4340 steel was selected as a work material which is widely used in die making, automobile and allied industries [2]. Its applications include aircraft engine mounts, propeller shafts, connecting rods, gear shafts, crane shafts, heavy forgings such as rotor shafts, discs, welded tubing applications, etc. It is a through hardenable medium alloy steel that can be hardened to 46HRc and is known for its toughness, tensile strength and fatigue strength and is less costly compared to high alloy steels. Considering its wide range of application in the industry this grade of steel was considered as the work material in the present investigation. Bars of 80 mm diameter and 380 mm length were used in the present investigation. The chemical

Table 1 – Composition of AISI 4340 steel.

	Elements						
	C	Mn	Si	Ni	Cr	Mo	Fe
% Composition	0.41	0.87	0.28	1.83	0.72	0.20	Rest

composition in weight % of AISI 4340 steel is available in Table 1.

3. Selection of tool

Multicoated hard metal inserts with sculptured rake face geometry with the specification SNMG 120408 MT TT5100 from Taegu Tec coated with TiC and TiCN were used as cutting tools in this investigation. The tool holder used had the specification PSBNR 2525 M12. The basic dimension of tool holder was 25 mm × 25 mm × 145 mm and the tool holder used is shown in Fig. 1. The selection of cutting tool and the tool holder was done based on the information available in the literature [2] and the recommendations of the leading cutting tool manufacturers, M/s. Taegutec India (P) Ltd. who were extending their technical/material support for this research work. The micro structure of tool Insert obtained using SEM-EDAX is shown in Figs. 2 and 3 which present the geometry, schematic view and cross section of tool insert. The dimensions of the insert coated with TiC and TiCN is shown in Table 2.

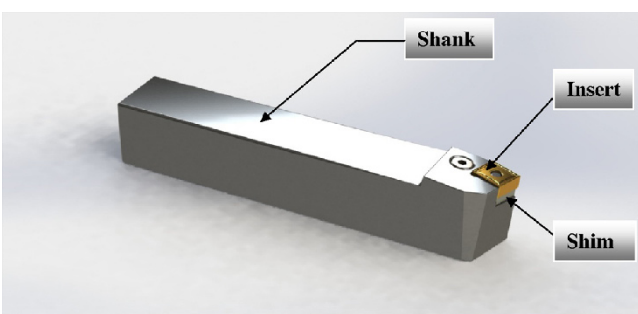

Fig. 1 – PSBNR 2525 M12 tool holder.

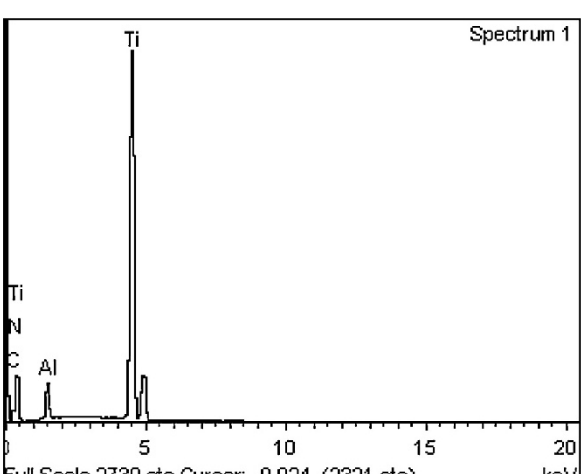

Fig. 2 – Microstructure of carbide insert.

Table 2 – Dimensions of the insert.

Designation	*L*	*d*	*R*	*t*
SNMG 120408 MT TT5100	11.9 mm	12.7 mm	0.8 mm	4.756 mm

4. Design and fabrication of MR fluid setup

Magnetorheological (MR) fluids belong to a class of controllable fluids which consist of a fluid impregnated with ferro magnetic particles. The essential characteristic of these fluids is their ability to reversibly change from a free-flowing, linear, viscous liquid to a semi-solid with controllable yield strength in milliseconds when exposed to a magnetic field. When exposed to a magnetic field, the suspended particles polarize and interact to form a structure aligned with the magnetic field that resists shear deformation or flow. This change in the material appears as a dramatic increase in apparent viscosity, or 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 [15]. The viscosity of MR fluid increases as the strength of the magnetic field increases and when the applied magnetic field vanishes, the MR fluid reverts to its previous, more fluid state. The transformation between the liquid to the semi solid phase takes place very fast, i.e. within few milliseconds [16].

A line sketch of the MR Fluid setup developed for this investigation is shown in Fig. 4. It consists of a plunger (P) which moves inside a cup containing MR fluid. MR fluid will be magnetized by passing current through the coil. Threads were cut at one 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. 4. Fig. 5 presents the photograph of the experimental setup. 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 of the plunger (*S*); (ii) the viscosity index of the fluid medium (p); (iii) size of the ferro magnetic particle (m); and (iv) the current through the coil (I). A dissembled view of the MR fluid setup is shown in Fig. 6.

5. Experimentation

It was decided to arrive at a set of MR fluid parameters namely the shape of the plunger (*S*), the viscosity index of the fluid medium (p), size of the ferro magnetic particle (m) and the current through the coil (I) to minimize tool wear. An 18 run experiment was designed based on Taguchi Technique [17] and the design matrix is presented in Table 3. The parameters which were varied at 3 levels is shown in Table 4. In this study, plungers of three different shape, namely cylindrical, conical and Inverted conical were used. Three fluids with the specifications SAE 20, SAE30 and SAE40 were considered based on the information available in the literature. Particles

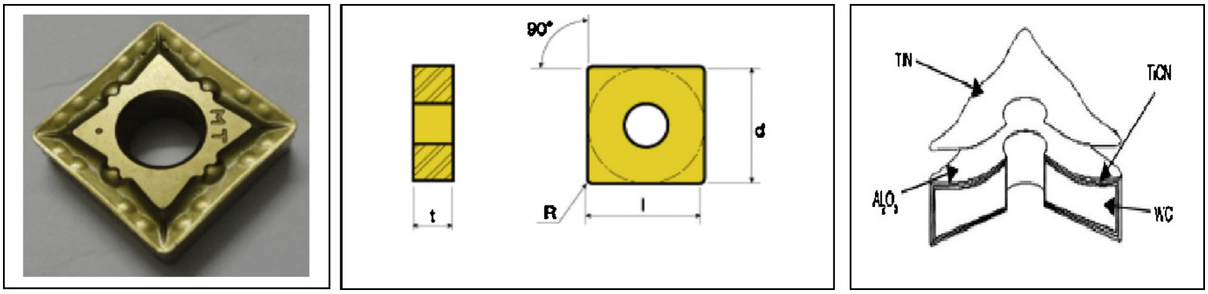

Fig. 3 – Geometry, schematic view and cross section of SNMG 120408 MT TT5100 insert.

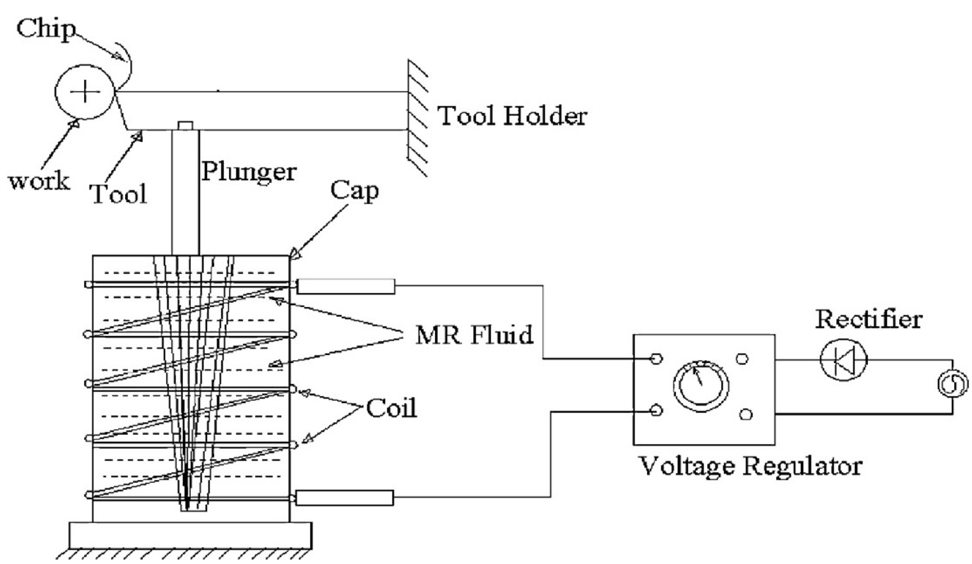

Fig. 4 – Line sketch of MR fluid setup.

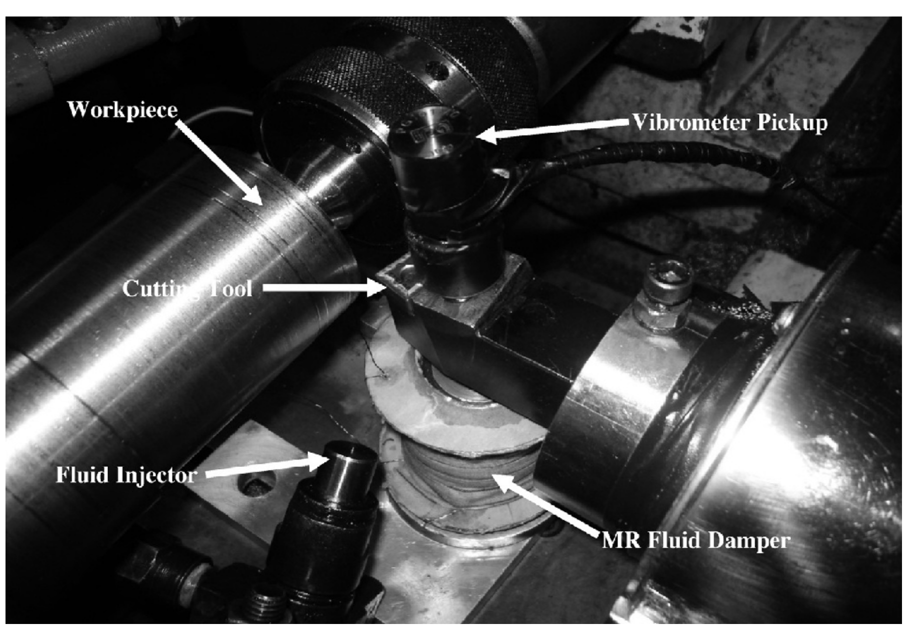

Fig. 5 – Photograph of the experimental setup.

Fig. 6 – Dissembled view of the MR fluid system.

Table 3 – Design matrix for the 18 run experiment.

Standard order	Factors				
	1	Current	Plunger	Viscosity	Ferro
1	AC	I1	S1	P1	M1
2	AC	I1	S2	P2	M2
3	AC	I1	S3	P3	M3
4	AC	I2	S1	P1	M2
5	AC	I2	S2	P2	M3
6	AC	I2	S3	P3	M1
7	AC	I3	S1	P2	M1
8	AC	I3	S2	P3	M2
9	AC	I3	S3	P1	M3
10	DC	I1	S1	P3	M3
11	DC	I1	S2	P1	M1
12	DC	I1	S3	P2	M2
13	DC	I2	S1	P2	M3
14	DC	I2	S2	P3	M1
15	DC	I2	S3	P1	M2
16	DC	I3	S1	P3	M2
17	DC	I3	S2	P1	M3
18	DC	I3	S3	P2	M1

S1, S2, S3 are the shape of the plungers, i.e. conical, cylindrical and inverted conical; P1, P2, P3 are the viscosity index of the fluid medium, i.e. SAE 20, 30, 40; M1, M2, M3 are size of the ferro magnetic particle, i.e. 45, 53, 75 μm; I1, I2, I3 are the current through the coil, i.e. AC and DC 10 V, 20 V, 30 V.

of 45, 53 and 75 μm sizes were selected in preparing the magnetorheological fluid. To magnetize the magnetorheological fluid, direct current and alternating current of 10 V, 20 V and 30 V were used. Since higher supply voltage may result in high temperatures and can lead to safety problems, supply voltage of maximum 30 V was used. Cutting experiments were conducted on a kirolskar turn master lathe. The relative significance of the operating parameters on the damping capability of the magnetorheological fluid system was determined by Response Table methodology using Qualitek Software.

In order to ensure the reliability of the results following precautions were taken.

1. Each experiment was replicated twice and the average result was considered for analysis.
2. Confirmatory experiments were carried out to check the correctness of the results obtained from the analysis.

During each experiment, the main cutting force was measured using a Kistler type 9257B dynamometer. Surface roughness was measured using Mahr TR100 surface roughness tester of type MarSurf GD 25. Once the surface was generated via the turning experiment, surface roughness value was measured and data were collected along the axis of the work piece. There are various simple surface roughness amplitude parameters used in industry, such as roughness average (R_a), root-mean square roughness (R_q), maximum peak-to-valley roughness (R_y or R_{max}), etc. The average roughness (R_a) is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length. R_a averages all peaks and valleys of the roughness profile, and then neutralizes the few outlying points so that the extreme points have no significant impact on the final results. Since it is a simple and effective method for monitoring surface texture and ensuring consistency in measurement of multiple surfaces, R_a was selected to express the surface roughness in this study.

Average flank wear was measured using Metzer tool maker's microscope. When the relief face of a cutting tool rubs against the workpiece, flank wear is created on this face and this type of tool wear is caused by an abrasion mechanism and it progresses gradually. Flank wear impairs the accuracy of the parts machined because it causes deflection of the cutting tool [18]. Flank wear is usually maximum at the extremities of the cutting edge and in the central zone the wear land it is fairly uniform. Flank wear land width (VB_B) shown in Fig. 7(b) is the criterion of tool life according to the ISO 3685 (1993) standard [19]. When the wear patterns formed on relief face of cutting tool are regular, $VB_B = 0.3$ mm is the criterion of tool life, and if the wear patterns formed on relief face of cutting tool are not regular, $VB_{Bmax} = 0.6$ mm is considered as the criterion of tool life.

Nose area of cutting tool is where the nose wear (VB_C) occurs. When severe nose wear is formed catastrophic tool failure can occur which will bring the life of the tool to a premature end [20]. Due to the limitation of the existing

Table 4 – Levels of parameters of the MR fluid.

Sl. no.	Parameters	LI	L2	L3
1	Shape of the plunger	Conical	Cylinder	Inverted conical
2	Viscosity index of the medium	SAE20	SAE 30	SAE 40
3	Particle size	45 μm	53 μm	75 μm
4	AC and DC current	10 V	20 V	30 V

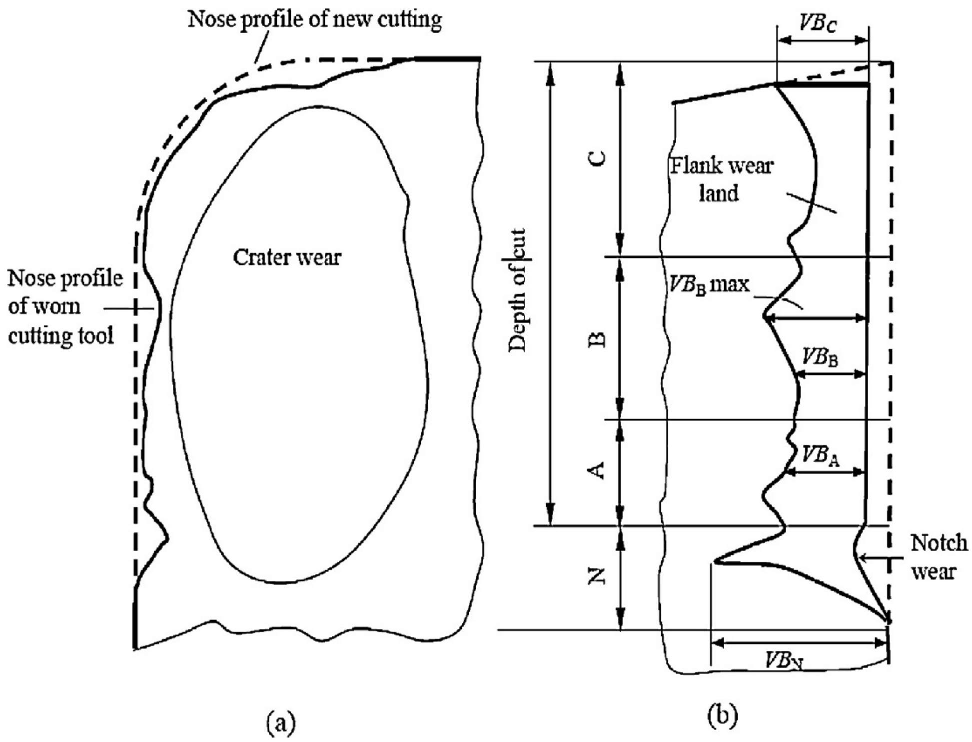

Fig. 7 – (a) Top view of crater wear and nose profile and (b) flank wear land and notch wear of cutting tool based on ISO 3685 [18].

methods, which cannot measure the nose wear fast and accurately, only few studies have been carried out in the past to investigate the effect of nose wear [21]. The reason VB_B is often used is that they can be measured in a fairly objective way while nose wear is difficult to quantify. Fortunately time history of each of these types of wear is similar. Also nose wear at the tip of the cutting edge is like flank wear and is driven by the same predominant mechanism, abrasion [22]. Hence in this study average flank wear land width (VB_B) was considered and measured.

Amplitude of tool vibration was measured using a piezoelectric vibrometer pickup mounted at the top of the tool holder. The cutting velocity was kept at 100 m/min, the feed at 0.12 mm/rev and the depth of cut at 1.2 mm. The pressure at fluid applicator was kept at 80 bar, the rate of fluid application at 8 ml/min, the frequency of pulsing at 500 pulses/min and fluid application was done at tool work interface.

6. Results and discussion

The relative significance of input parameters on tool wear is shown in Figs. 8 and 9 which present the relative significance of the input parameters on cutting force. The relative significance of input parameter on surface roughness and amplitude of tool vibration are shown in Figs. 10 and 11, respectively.

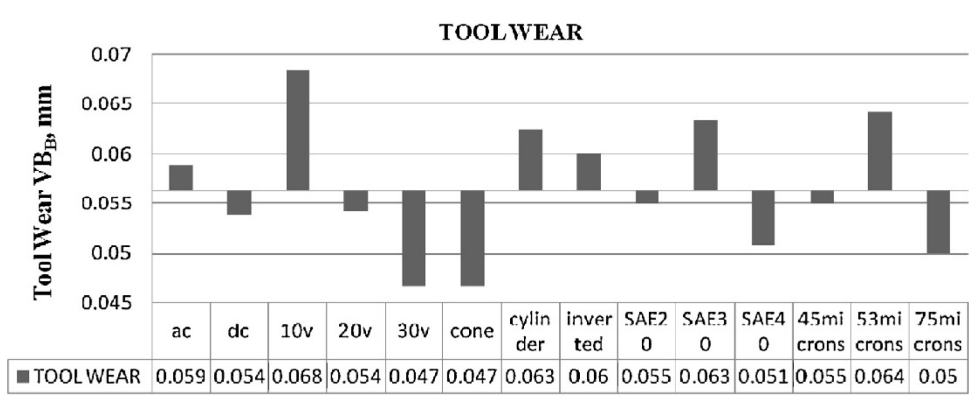

Fig. 8 – Relative significance of input parameters on tool wear.

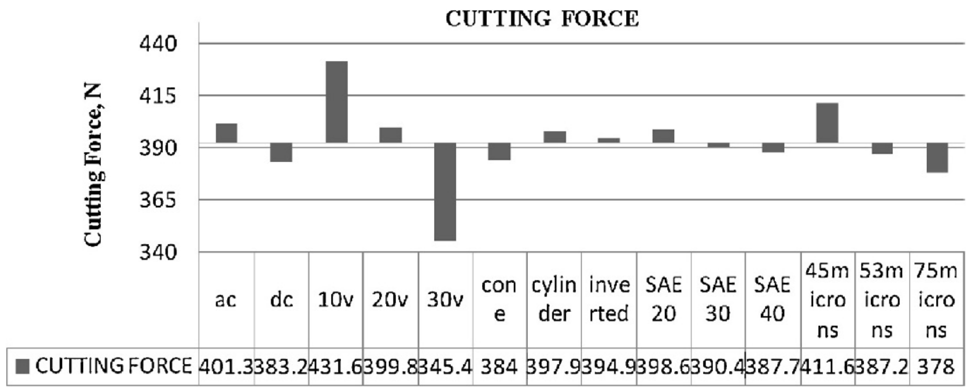

Fig. 9 – Relative significance of input parameters on cutting force.

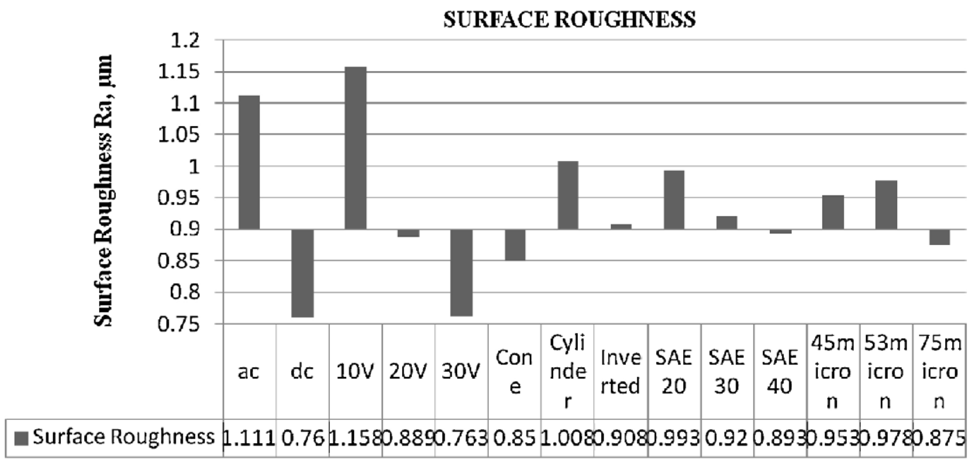

Fig. 10 – Relative significance of input parameters on surface roughness.

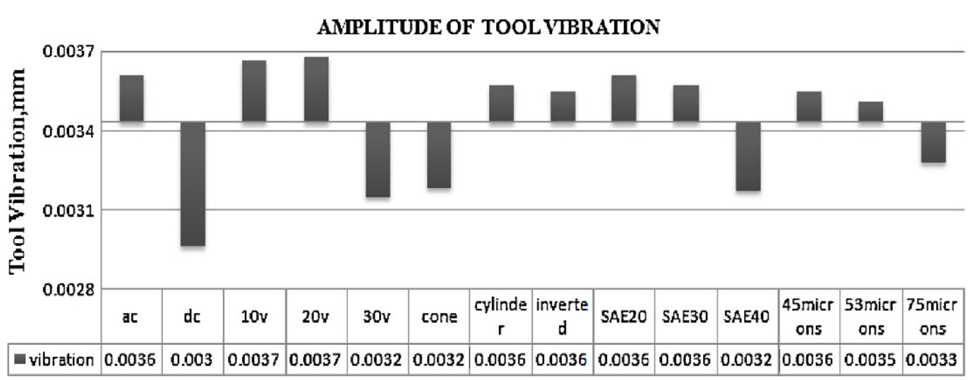

Fig. 11 – Relative significance of input parameters on amplitude of tool vibration.

The experimental results were analyzed using Qualitek-4 and the levels of input parameters for achieving minimum tool wear, tool vibration, cutting force and surface roughness are summarized in Table 5.

From Table 5, it is observed that for minimizing tool wear and for achieving better cutting performance, the voltage should be kept at level 3 (30 V), direct current is to be used in the coil (level 2), a cone shaped plunger should be used (level 1), the particle size should be at level 3 (75 μm) and the fluid used should have a viscosity index at level 3 (SAE40).

When alternating current is used, the field produced by the coil fluctuates with the frequency of the alternating current which leads to an unstable distribution/orientation of the magnetic particles around the plunger with lower damping capability. But when direct current is used, there is no fluctuation in the magnetic field and this leads to a more stable orientation of magnetic particles around the plunger which enhances its damping capability. Also it is seen that the supply voltage at high level (30 V) offered better damping capability. The strength of the magnetic field depends on the

Table 5 – Levels of input parameters for getting optimum performance.

Sl. no.	Objective	Current	Voltage	Shape of plunger	Viscosity	Size of ferro particles
1	To minimize Tool Wear VB_B	L2 (DC)	L3 (30 V)	L1 (conical)	L3 (40)	L3 (75)
2	To minimize Cutting Force	L2 (DC)	L3 (30 V)	L1 (conical)	L3 (40)	L3 (75)
3	To minimize Surface Roughness R_a	L2 (DC)	L3 (30 V)	L1 (conical)	L3 (40)	L3 (75)
4	To minimize Amplitude of Tool Vibration	L2 (DC)	L3 (30 V)	L1 (conical)	L3 (40)	L3 (75)

supply voltage. When the supply voltage is higher, strength of the magnetic field will be high and better will be the damping ability. But an applied voltage at very high magnitude should also be avoided as this may lead to the condition wherein the MR fluid will become a solid mass and loses its damping capability altogether. Moreover higher supply voltage may also result in high temperatures and can lead to safety problems. It is observed that a plunger with conical shape can offer better cutting performance when compared to other geometries. This shape helps in better anchoring of the plunger inside the MR fluid. When the plunger has a conical shape, it resists the movement in the downward direction better when compared to a plunger with cylindrical and inverted conical shapes.

A magnetorheological fluid made of oil with viscosity index at level 3 (SAE 40) provided better cutting performance as this oil can offer higher resistance to the movement of the plunger. Finally it is seen that magnetic particle in the MR fluid should have certain minimum size to offer better performance. If the size of the particles in the MR fluid is very small, there is a possibility of magnetic materials sticking together to form a solid mass when magnetized. But if the size of the particle is sufficiently high (75 μm), the tendency to form a solid block reduces. There will be a good distribution of the magnetized particles with the fluid occupying the region in between and this distribution of magnetized particles in a pool of the fluid provides better resistance to the movement of the plunger which leads to reduction in tool wear and improvement in surface finish.

Cutting experiments were conducted with the input parameters kept at levels as indicated in Table 5 and the performance was compared with the cutting performance during conventional minimal fluid application without magnetorheological fluid system and also with dry hard turning. Comparison of the cutting performance for the three cases is presented in Table 6.

From the results it was observed that the presence of MR fluid system can suppress the amplitude of tool vibration by 86.6%, reduce tool wear by 57%, cutting force by 22.4% and improve surface finish by 44.4% when compared with turning without magnetorheological fluid system (but with minimal fluid application) under the same cutting conditions.

The most prominent component of the cutting force in turning operation is the main cutting force and it acts in the downward direction. The increase in the main cutting force component during hard machining can be considered as a measure of the deterioration of the lubricating ability of the cutting fluid which affects the cutting performance [23]. Any system that can oppose the movement of the tool in the downward direction can provide better damping. In this investigation, the main cutting force component is reduced effectively due to the presence of magnetorheological fluid which in turn leads to a stable cutting operation with reduced tool wear and improved surface finish.

In general, the best way to solve a tool vibration problem is to increase the stiffness of the system. When ferro particles of 75 μm size mixed with an oil of viscosity index specified by SAE40 and magnetized with direct current provided with a cone type plunger, main cutting force was reduced by 22.4%. In the case of dry turning, the cutting force was 466.35 N and during turning with minimal fluid application the force reduced to 438.5 N, whereas during minimal fluid application along with magnetorheological system, the cutting force was as low as 340.3 N. This reduction in cutting force reduces the total energy required to perform cutting operation. The damping force created by the effect of magnetorheological fluid increases the rigidity of the tool which reduces the amplitude of tool vibration by 86.6%.

When the bouncing of the tool in and out of the work piece decreases, there is a reduction in the irregularities of the surface generated. The average length between the peaks and valleys and the deviation from the mean line on the entire surface within the sampling length when the magnetorheological fluid was not used was found to be 0.9 μm and when the tool was provided with a magnetorheological fluid it was found to be 0.5 μm. The result clearly demonstrates that the presence of magnetorheological fluid can reduce surface roughness effectively. This smooth surface limits the risk of crack initiation [24,25] and reduces tool wear effectively through the reduction in cutting force and tool vibration parameters. From the experimental results it was observed that the magnetorheological fluid reduces tool wear by 57% when compared to a condition in

Table 6 – Comparison of performance with MR fluid and without MR fluid under the same cutting conditions.

Parameters	With MR fluid during minimal fluid application	Without MR fluid during minimal fluid application	Without MR fluid during dry hard turning
Tool wear VB_B (mm)	0.030	0.070	0.081
Cutting force (N)	340.30	438.50	466.35
Surface roughness R_a (μm)	0.50	0.90	0.98
Amplitude of tool vibration (mm)	0.0020	0.0150	0.0173

which the tool holder was not provided with a magnetorheological fluid system.

7. Conclusions

In this study, an attempt was made to investigate the effect of a magnetorheological fluid system on tool wear during hard turning of AISI 4340 steel with minimal fluid application using hard metal inserts with sculptured rake face. A magnetorheological fluid system has been developed and series of experiments have been carried out which lead to the following conclusions:

1. A magnetorheological fluid scheme can reduce tool wear effectively during hard turning with minimal fluid application.
2. For achieving the best performance the magnetorheological fluid is to be prepared with ferro particles of 75 μm size mixed with an oil of viscosity index specified by SAE40. A conical plunger is to be used and a direct current is to be used for energizing the magnetic field.
3. The presence of magnetorheological fluid system can bring forth 22.4% reduction in cutting force, 44.4% improvement in surface finish and 57% reduction in tool wear during hard turning with minimal fluid application and commercialization of this technique is sure to benefit the metal cutting industry.

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