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Influence of magnetorheological elastomer on tool vibration and cutting performance during boring of hardened AISI4340 steel †

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Abstract

During boring process, tool vibration is a major concern due to its overhanging length, which results in high cutting force, poor surface finish, and increase in tool wear. To suppress tool vibration and improve cutting performance, a novel technique in rheological fluid was designed and developed. In this work, a magnetorheological elastomer (MRE) was developed, and parameters, such as piston location, current intensity, and coil winding direction, were considered. Cutting experiments were conducted to obtain a set of parameters that can efficiently control vibration during boring of hardened AISI 4340 steel. Taguchi method was used to optimize the cutting condition, and findings show that the cutting tool embedded with the MRE reduced tool vibration and effectively increased cutting performance.

Keywords: Tool vibration; Magnetorheological elastomer (MRE); Hard boring; Surface finish; Cutting force

1. Introduction

Recently, the manufacturing industries are focused on achieving high quality, good dimensional accuracy, high production rate, minimal tool wear, cost saving, and increased environmental safety. Most of these factors are affected by tool vibration in metal cutting. Quintana and Ciurana [1] proposed that the poor dynamic stiffness of cutting tool results in increased tool vibration, which affects productivity and quantity during machining. The dynamic interaction between the cutting process and structures leads to tool vibration. Surface wave and tool vibration result in varying cutting forces, which excite the machine and workpiece. Tool vibration leads to poor surface finish and increase in tool wear [2]. Additionally, findings show that the poor rigidity of the tool holder largely causes tool vibration during boring, and any scheme that provides suitable rigidity will efficiently control tool vibration. Paul et al. [3] used a magnetorheological fluid (MRF) damper during turning to reduce tool vibration and effectively optimized the control of rheological parameters. Although the fluid damper has achieved notable progress in controlling tool vibration, certain factors still affect the stability of MRF. Factors, such as an increase in temperature over extended periods of time and settling of iron particles, are of great concern in terms of MRFs. The influence of nanoparticles in MRFs was reported to solve these issues to a certain extent, but not in entirety [4]. Thus, to solve this problem, researchers shifted their focus toward the magnetorheological elastomer (MRE), which was considered an optimal tool for controlling vibration because it can solve the problems faced by MRF, such as deposition, sealing, and environmental issues [5]. However, a study that investigates the influence of MRE during boring has yet to be conducted.

An MRE is part of the MR family, which consists of a composite material with magnetic particles arranged within a non-magnetic elastomer matrix [6]. When magnetic field is applied, the particles exhibit an MR effect, which is a field-dependent material property, to the material, and it is a controllable modulus and damping. When the magnetic field is applied to the soft elastomer material, it turns semi-solid and returns to its original position when magnetic field is removed [7]. MRE is composed of natural or silicon rubber in accordance with the needs and consists of iron particles, a rubber matrix, and additives [8, 9]. To avoid the problems faced with MRF, moisture content from the particle surface in MRE is removed via the curing process to render the particles hydrophobic [10]. In MRE materials, silicon oil is used as an additive, which enters the matrix and increases the space between molecular matrixes. Silicon oil increases plasticity and fluidity in the matrix, which contributes to the stable properties of MRE materials [11]. Using MRE actively reduces vibration and provides enhanced damping [12].

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In designing an experiment, the Taguchi method is considered as a powerful tool for optimizing design in performance, cost, and quality. Currently, manufacturing industries are using this method due to advancements in the Taguchi technique [13]. In this study, MRE was developed to suppress tool vibration during boring of hardened steel. Cutting experiments were designed on the basis of the Taguchi technique and were conducted for a set of electrical and compositional parameters during boring of AISI 4340 steel with 45 HRC to study the effect on cutting performance and tool vibration. Results show that the MRE reduced tool vibration and notably increased cutting performance.

2. Development of MRE

Smart materials can alter one or more of their properties with the application of an external source in a controlled manner. This change of properties due to an external force will be useful for generating the required damping force to a vibrating structure. Among the smart materials used, MRE is an effective rheological material that controls vibration through changes in the stiffness of the vibrating structure. The MRE belongs to a class of solids that consist of a polymeric matrix with embedded iron particles. As a result of this composite micro-structure, the rheological elastomer becomes activated when the coil is energized and provides resistance to the movement of the tool holder through a piston, thereby suppressing tool vibration. During the machining process, the damping ability of the MRE can be altered by varying the magnitude of the current, winding used, and piston position. MRE consists of a silicon-based rubber in liquid form mixed with iron particles. These materials were placed inside a container with the required ratio by weight. After adding a curing agent to the mixture and stirring well to remove air gaps from the mixture, the combination was poured into a mold. For the alignment of the iron particle, the mold with the mixture was kept under a magnetic field for 24 h. Table 1 provides the specification of the MRE that was used. When a magnetic field is applied to the particle mixture, a particle chain structure is formed, which is locked during the curing process, and a viscoelastic material is obtained [6, 14]. In addition, the elastic modulus in that particular direction will change on the basis of the strength of the magnetic field and internal distribution of particles when exposed to the magnetic field. The MRE used in this investigation reduced the amplitude of vibration by 86.6 %, and from this reduction, we infer that the MRE removes energy from the system and helps reduce the quantum of energy that is produced by the system. This mechanism supports the function of MRE as a damper in suppressing tool vibration.

Fig. 1 depicts a line sketch of the MRE. The setup for the MRE consists of a plunger (P), which moves inside a cylinder that contains the MRE that is magnetized by a passing current through a coil wound up over the cylinder. Threads were cut in one end of the plunger that matches the threads cut on the hole of the tool holder, such that the plunger can be held rigidly with the tool holder. The materials used for fabricating MRE are composed of OHNS.

Table 1. MRE specification.

Rheological parameters	Composition
Mixing proportion of curing agent (%)	2 %
Iron particle	68 %
Silicon oil	30 %
Curing time	24 hrs

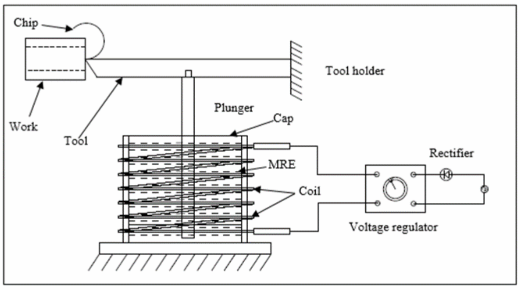

Fig. 1. Line sketch of MRE in boring process.

3. Experimental setup

Experiments were carried out on a Kirloskar turn master-35 lathe to study the effect of MRE on tool vibration, surface roughness, and cutting force during boring process. Fig. 2 illustrates the setup used in this investigation.

In lathe, the machining accuracy of the machine tool is greatly influenced by the rigidity of the machine, tool, and workpiece system. In summary, the rigidity of the machine tool depends on the rigidity with which various units are clamped. To ensure this condition, joints among various structural elements were made as rigid as possible, housings were provided for individual units/assemblies, and smooth provision was relatively provided to support and move the workpiece and tool. In this experimental work, the initial vibration in the machine tool structures that was measured before the commencement of machining was found to be zero. The same condition was maintained during the entire experimental work of the machine tool. In addition, the damper that was connected to the tool holder was clamped by attaching a rigid plate to the carriage.

3.1 Selection of cutting tool and workpiece

In this paper, AISI 4340 is used as the workpiece material, which was hardened via heat treatment process [15]. This steel has a wide range of application over automobile and associated industries because of its hardenability. A bar with an outer length of 80 mm, inner diameter of 40 mm, and length of 100 mm is used in this investigation. The AISI 4340 steel in

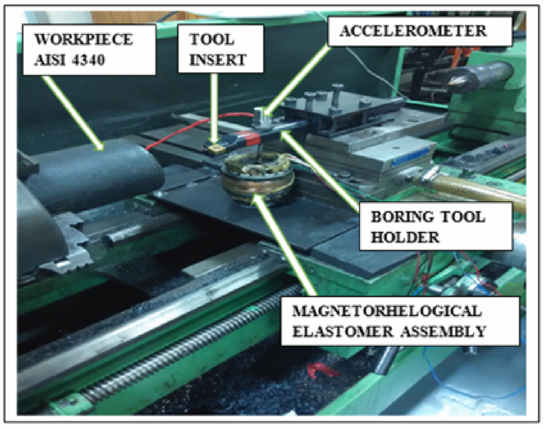

Fig. 2. Photograph of experimental setup.

weight percent is 0.41 % C, 0.87 % Mn, 0.28 % Si, 1.83 % Ni, 0.72 % Cr and 0.20 % Mo, and the remainder of the chemical composition is Fe [16]. The boring tool holder used is S25T PCLNR 12F3, which consists of an insert, tool shank, and sim. The insert, which has a specification of CNMG 120408 MT TT5100 from Taegu Tec, was used [17].

3.2 Design of experiments

A 27-run experiment was designed in which the input variables, namely, piston position, coil winding direction, and current magnitude, were varied at three levels [18]. Three-level tests for each factor were used because the variables considered are multilevel ones, and the effect of their outcomes is nonlinear. In this respect, the 27-run experiment was performed, and experiments were conducted with three replications for each run. The levels for coil winding and current were considered on the basis of the available information in the Ref. [2]. In addition, three piston positions (70, 85 and 100 mm) from tool edge were selected on the basis of the tool comfort, work handling, geometry constraint of the tool post, and chuck. Furthermore, the piston position in the damper cannot be altered below 70 mm and beyond 100 mm because performing the boring operation is practically improbable, which results in interference to the chuck, tool, and workpiece.

In this paper, the S:N ratio was used to measure the quality characteristics that deviate from the desired values of the experimental results. The S:N ratio for each level of the process parameters is computed on the basis of the S:N analysis. Regardless of the category of the quality characteristic, a high S:N ratio corresponds to improved quality characteristics. Therefore, the optimal level of the process parameters is that with the largest S:N ratio. Eq. (1) defines the S:N ratio η, which is used to measure the quality characteristics that deviate from the desired values. Typically, the analysis of the S:N ratio reveals three categories of quality characteristic, namely, the-lower-the-better, the-higher-the-better, and the nominal-the-better. In the present investigation, the lower-the-better quality characteristic is selected using the MSD equation and is presented in Eq. (2):

$$\eta = -10\log(\text{MSD}), \tag{1}$$

$$\text{M.S.D} = \frac{1}{M}\sum_{i=1}^{m} S_i^2 . \tag{2}$$

3.3 Cutting parameters and measurement

In this investigation, performance indices, such as main cutting force, tool vibration, and surface roughness, were determined for each experiment. The cutting force was measured using a Kistler tool force dynamometer, and surface roughness (Ra) was calculated using a Mahr TR100 surface roughness tester of type Mar Surf GD 25. The amplitude of tool vibration was measured using a piezoelectric type accelerometer (Dytran 3055D2) with a sensitivity of 96.69 mV/g, which was mounted on the top surface of the tool holder. The measured value is displayed in millimeter. The sensor used was calibrated by the manufacturer (LMS) as per the international standards with an accuracy of ±0.5 %. Although this sensor is capable of measuring acceleration (m/s^2), velocity (m/s) and displacement (mm), the displacement parameter was measured because it is the most important parameter that influences the stability of the cutting tool, the lack of which results in progressive tool wear and imbalance in machine tools. In the present investigation, the 27-run experiment was based on the Taguchi method to study the effect of MRE on a boring bar for controlling tool vibration. We decided to set the following MRE parameters: plunger position (S) on the tool from its edge (70, 85 and 100 mm), coil winding direction (W) (winding perpendicular to the axis, winding parallel to the axis, and a combination of winding parallel and perpendicular to the axis), and current (C) supplied in Amps (1, 2 and 3 A) to reduce tool vibration.

The damper was located at three positions (70, 85 and 100 mm) from the tool edge. These positions were selected on the basis of the geometry constraint of the tool post and chuck, further tool comfort, and work handling. Moreover, the piston position cannot be altered below 70 mm and beyond 100 mm because it is practically improbable to perform machining during boring, which further results in interference of the chuck tool and workpiece. Hence, these parameter levels were considered. The parameters of MRE were varied at three levels, as shown in Table 2. The cutting velocity (100 m/min), feed (0.06 mm/min), and depth of cut (0.5 mm) were kept constant on the basis of the abovementioned preliminary investigation. Cutting experiments were conducted in dry condition with an average of three replications for each run, and each experiment lasted for 2 min.

4. Results and discussion

Cutting experiments were conducted with the input parameters retained at specific levels (Table 2). The experimental results and S:N ratio for tool vibration, cutting force, and sur-

Table 2. Levels of parameters of MRE damper.

S. No	Parameters	L_1	L_2	L_3
1	Piston position	70 mm (S_1)	85 mm (S_2)	100 mm (S_3)
2	Coil winding	Winding perpendicular to the axis (W_1)	Winding parallel to the axis (W_2)	Combination of winding parallel and perpendicular to the axis (W_3)
3	Current	1 A (C_1)	2 A (C_2)	3 A (C_3)

Table 3. Experimental results and S:N ratio for tool vibration, cutting force, and surface roughness.

Standard order	Factor			Tool vibration/mm	S:N ratio for tool vibration (dB)	Cutting force/N	S:N ratio for cutting force (dB)	Surface roughness/μm	S:N ratio for surface roughness (dB)
	Piston position	Coil winding	Current						
1	S_1	W_1	C_1	1.143333	−1.16345	201	−46.0639	0.808667	1.844606
2	S_1	W_1	C_2	1.175222	−1.4024	68	−36.6502	0.728667	2.749418
3	S_1	W_1	C_3	0.510706	5.836581	102.6	−40.2229	0.609333	4.302906
4	S_1	W_2	C_1	1.970667	−5.89226	126	−42.0074	0.753333	2.46026
5	S_1	W_2	C_2	1.088222	−0.73435	141	−42.9844	1.158	−1.27417
6	S_1	W_2	C_3	0.656667	3.653096	240	−47.6042	0.584	4.671743
7	S_1	W_3	C_1	0.975533	0.215161	208	−46.3613	0.437667	7.177124
8	S_1	W_3	C_2	1.112125	−0.92307	47	−33.442	0.285667	10.8828
9	S_1	W_3	C_3	1.16275	−1.30973	103	−40.2567	0.355	8.995433
10	S_2	W_1	C_1	2.294571	−7.21403	144	−43.1672	0.741	2.603636
11	S_2	W_1	C_2	1.505308	−3.55251	300	−49.5424	1.025667	−0.22013
12	S_2	W_1	C_3	1.858667	−5.38403	298	−49.4843	1.014667	−0.12647
13	S_2	W_2	C_1	1.609917	−4.13607	302	−49.6001	0.804	1.894879
14	S_2	W_2	C_2	1.0879	−0.73178	130	−42.2789	0.621	4.138168
15	S_2	W_2	C_3	0.617417	4.188428	21.5	−26.6488	0.479667	6.381203
16	S_2	W_3	C_1	0.609077	4.306556	170	−44.609	0.768667	2.285235
17	S_2	W_3	C_2	0.999917	0.000721	151	−43.5795	0.74688	2.534983
18	S_2	W_3	C_3	0.781111	2.145745	222	−46.9271	0.633667	3.962778
19	S_3	W_1	C_1	2.486571	−7.91202	239	−47.568	0.92	0.724243
20	S_3	W_1	C_2	1.963688	−5.86145	324	−50.2109	0.743667	2.57243
21	S_3	W_1	C_3	1.8345	−5.27035	286	−49.1273	0.668	3.504471
22	S_3	W_2	C_1	1.5819	−3.98358	259	−48.266	0.787	2.080505
23	S_3	W_2	C_2	1.580417	−3.97543	390	−51.8213	0.94667	0.476028
24	S_3	W_2	C_3	1.292188	−2.22651	268	−48.5627	0.838333	1.531669
25	S_3	W_3	C_1	1.653333	−4.36721	245	−47.7833	0.998667	0.011586
26	S_3	W_3	C_2	1.297313	−2.2609	296	−49.4258	0.802667	1.909292
27	S_3	W_3	C_3	1.127667	−1.04362	28.9	−29.218	0.779333	2.165539

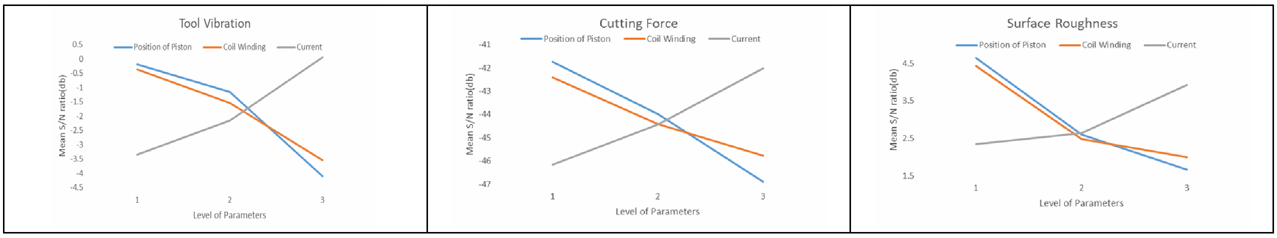

Fig. 3. S:N graph for tool vibration, cutting force, and surface roughness.

face roughness that were obtained using Eqs. (1) and (2) are displayed in Table 3. Results show that tool vibration was varied and suppressed. In addition, cutting performance was enhanced when these rheological parameters were altered.

Table 4. S:N ratio (dB) table for tool vibration, cutting force, and surface roughness.

S. No	Cutting parameter	S:N ratio (dB) for tool vibration			S:N ratio (dB) for cutting force			S:N ratio (dB) for surface roughness		
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
1	Piston position	−0.19116	−1.15300	−4.1001	−41.73	−43.98	−46.89	4.646	2.606	1.664
2	Coil winding	−0.35959	−1.53761	−3.5470	−42.40	−44.42	−45.78	4.436	2.484	1.995
3	Current	−3.34966	−2.16013	0.06551	−46.16	−44.44	−42.01	2.342	2.641	3.932

Table 5. ANOVA for tool vibration.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %
Piston position	2	3.9843	3.9843	1.9922	34.10	0.000	23.12
Coil winding	2	5.4468	5.4468	2.7234	46.62	0.000	31.61
Current	2	6.6295	6.6295	3.3148	56.74	0.000	38.47
Error	20	1.1684	1.1684	0.0584	-	-	6.78
Total	26	17.2291	-	-	-	-	-

Table 6. ANOVA for cutting force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %
Piston position	2	91592	91592	45796	21.82	0.000	21.79
Coil winding	2	93897	93897	46948	22.37	0.000	22.34
Current	2	192690	192690	96345	45.91	0.000	45.86
Error	20	41970	41970	2099	-	-	9.98
Total	26	420148	-	-	-	-	-

Table 7. ANOVA for surface roughness.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %
Piston position	2	7.6916	135245	3.8458	46.69	0.000	27.97
Coil winding	2	8.1365	101683	4.0682	49.39	0.000	29.59
Current	2	10.0188	217301	5.0094	60.81	0.000	36.43
Error	20	1.6475	42250	0.0824	-	-	5.99
Total	26	27.4944	-	-	-	-	-

Table 4 summarizes the S:N ratio for each level of the cutting parameters, such as tool vibration, cutting force, and surface roughness. Fig. 3 illustrates the S:N graph for tool vibration, cutting force, and surface roughness and shows that the piston position, coil winding, and current should be retained at levels 1, 1 and 3 for optimum results, respectively. The results further reveal that the piston position, coil winding, and current intensity should be at levels S_1 (70 mm), W_1 (vertical) and C_3 (max level), respectively, to minimize tool vibration and achieve enhanced cutting performance. Analysis of variance (ANOVA) was performed using MINITAB 16 software to determine the percentage of influence of individual parameters on tool vibration, cutting force, and surface roughness. Tables 5-7 display the analysis results, which lead to the identification of important parameters. On the basis of the ANOVA results, the tables reveal that the current magnitude is the most important parameter that influences the output parameters (tool vibration, cutting force, and surface roughness) followed by coil winding and piston position. In addition, the results led to a set of parameters that can be used to minimize tool vibration, cutting force, and surface roughness, as shown in Table 8.

From the result, we infer that the location of the damper on tool holder has a notable influence on damping capability. In this investigation, three locations of the damper were discussed (70, 85 and 100 mm). We note that the plunger damper straddling at 70 mm from the tool edge provides better resistance to tool vibration than the positions at 85 and 100 mm. However, when the plunger is straddling in the 85 and 100 mm positions, the damping force will create an unbalancing effect, and the damped force is combined with the main cutting force, which resulted in high vibration and a reduction in the cutting performances. The result also shows that the main cutting force decreases when the plunger position is 70 mm away from the edge of the tool holder. When the MRE damper setup is mounted considerably far from the tool edge, the tool holder bounces and leads to an increase in the main cutting force. However, when the MRE damper is mounted near to the tool edge, bouncing in the tool holder is reduced, and the main cutting force is decreased. This setup results in improved balancing and MRE results in the development of damping force, which absorbs the main cutting force during cutting operation. When the bouncing of the tool decreases, the irregularities in the workpiece surface are also decreased.

In general, change in stiffness affects cutting tool rigidity, which in turn affects tool life and vibration. When the stiffness of the cutting tool increases, damping will be enhanced, and energy required for machining operation will be reduced. The dynamic nature of the main cutting force that acts on the tool holder during hard boring operations decreases the cutting tool vibration due to the increased stiffness of the machine tool. We argue that the presence of magnetic particles increases the damping capacity with the increase in current intensity (3 A). If the current increases beyond the limit, then an increase in temperature is possible, which will reduce damping capacity.

Table 8. Levels of input parameters for obtaining optimum parameters.

S. No	Objective	Piston position	Coil winding	Current
1	To minimize vibration	$L_1(S_1)$	$L_1(W_1)$	$L_3(C_3)$
2	To minimize cutting force	$L_1(S_1)$	$L_1(W_1)$	$L_3(C_3)$
3	To minimize surface roughness	$L_1(S_1)$	$L_1(W_1)$	$L_3(C_3)$

Table 9. Comparison of performance with and without MRE damper.

S. No	Performance parameters	With MRE damper	Without MRE damper	Improvement
1	Vibration (mm)	1.33247	2.48657	86.6 %
2	Cutting force(N)	196.703	312	58.61 %
3	Surface roughness (μm)	0.7422	1.012	36.35 %

In addition, when the current is applied to the coil that is wound up in the vertical direction, the damping force developed will be higher than that of the coil that is wound up in the axial direction. This high damping force resists the main cutting force that is generated during machining, which results in less magnitude of tool vibration. Moreover, when the coil is wound up in the axial direction, the generation of low magnitude of damping forces will be unable to resist the main cutting force, thereby only marginally suppressing tool vibration.

Table 8 shows that the direct current with maximum intensity should be used along with the plunger positioned at the minimum distance from the tool edge with the coil wound up in the vertical direction to reduce tool vibration and achieve enhanced cutting performance.

Table 9 shows a comparison of the cutting performance for tool holder with and without MRE damper. MRE can suppress tool vibration by 86.6 %, reduce cutting force by 58.61 %, and decrease surface roughness by 36.35 %. The silicon oil used in MRE has excellent thermal and shear resistance, which help in providing enhanced damping capability over a wide range of temperature. When a high current was applied to the elastomer, the temperature gradually increased. As a result, silicon oil that was present in the elastomer withstood the temperature effect and increased the damping capability. The mechanism involved in the elastomer offered consistency and positive viscosity characteristics to suppress vibration. It was also inferred that the elastomer, which has outstanding resistive capacity at high temperature, has improved capability for absorbing vibration consistency over a wide temperature range due to the varying current intensities. The MRE used in this investigation reduced the vibration amplitude by 86.6 %. On the basis of this reduction, we argue that the MRE takes energy out of the system and helps to reduce the quantum of energy produced by the system. Thus, the MRE is considered to act as a damper in suppressing tool vibration.

5. Conclusion

In the present investigation, the MRE damper was designed, developed, and verified to study its effect on tool vibration, surface roughness, and cutting force during hard boring. A 27-run Taguchi experiment was conducted and optimized using the Taguchi method, which provided a methodical and effective approach for the design optimization of the cutting parameters compared with other optimization techniques. The results obtained using the MRE damper was compared with conventional operation without the MRE damper during hard boring operation. From the present study, the following conclusions were drawn.

(1) The vibration, which occurs due to the interaction of cutting process and machine tool dynamics during boring, can be suppressed by adding the MRE to the tool holder. The results show that the variation in tool vibration was effective when the MRE was attached to the tool holder, which suppressed vibration by 86.6 %.

(2) To attain enhanced cutting performance, such as reduced tool vibration, cutting force, and surface roughness, the MRE system should be designed with the plunger located 70 mm from the tool edge, coil winded over the damper perpendicular to the axis, and current supplied in 3 A.

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