Improvement of Surface Quality using Magneto-Rheological Fluid (MRF) Boring Bar

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Abstract

Boring bars with a large length-to-diameter ratio chatter under productive cutting conditions, which lead to poor surface finish and violation of part tolerances. Chatter suppression in machining permits higher productivity and better surface finishes. The MR fluid, which changes stiffness and undergoes a phase transformation when subjected to an external magnetic field, is applied to adjust the stiffness of the boring bar and suppress chatter. The stiffness and energy dissipation properties of the MR fluid boring bar can be adjusted by varying the strength of the applied magnetic field. This research work is intended to improve the surface quality of various materials at two different speeds with magneto-rheological fluid (MRF) boring bar during boring process.

Keywords: Chatter, Surface finish, Boring Process, MRF Boring Bar, Lateral Stiffness.
INTRODUCTION

Machining is one of the most common processes for material removal in industry. Cutting operations such as turning, milling, boring, and grinding, are sometimes associated with degrading vibrations resulting in poor surface quality, decreased removal rate and accelerated tool wear [1]. Chatter or self-excited vibration is the most significant type of vibration in machining operations. Regeneration and mode coupling are the main phenomena leading to chatter, the former being the more detrimental for machining operations. Some works on chatter analysis are briefly summarized below.

The problem of vibration becomes more significant when a flexible tool is used, as in the case of internal turning operations. Boring operations need long and slender bars to machine the internal zones of the work piece. Geometrical requirements of the tool are related to degrading vibrations, influencing not only surface quality, but also tool durability and productivity. Vibrations also have environmental consequences due to the high noise levels produced. The interest of these processes in industry and the special geometry of the tool have motivated the development of numerous works investigating chatter in boring operations. The stability behavior of a slender boring bar was studied by Parker [2]. The boring bar was modeled as a two-degree-of-freedom mass-spring-damper system. The mode coupling was experimentally analyzed for a range of cutting parameters. The analysis of boring-bar vibrations is usually based on the lower-order bending modes of the clamped boring bar [3], although the clamping conditions of the bar also influences its dynamic properties [4]. Zhang and Kapoor [5] developed a two-degree-of-freedom model of a clamped boring bar with four cutting-force components. Andren et al. [6] compared an analytical Euler–Bernoulli model with a time-series approach to investigate boring-bar chatter.

Not only characteristics of the boring bar such as clamping conditions have been analyzed. Different authors [7–12] have also focused attention on the geometrical details of the insert influencing the cutting force and the dynamic behavior of the boring bar.

Different strategies have been developed to avoid or diminish vibrations in boring operations. Improved tool holder and clamping design [4] have demonstrated the ability to improve the dynamic behavior of the system. On the other hand, continuous improvement has been achieved in the chatter control of boring, including sophisticated methods, such as the use of active dynamic absorbers [13–16] and passive dynamic absorbers [17–22]. However, the use of electro-rheological [23] and magneto-rheological fluids [24] is a simple solution and it is still a promising field of research for chatter suppression, not only in boring operations.

Semi-active chatter suppression can improve stability by changing the inherent stiffness and dynamic damping parameters of a system [23]. Semi-active chatter suppression not only has better damping effectiveness than the passive mode, but also has lower power and cost requirements than active suppression [25]. A semi-active chatter suppression method employing the MR fluid is investigated in this study. MR
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The improvement of surface quality using Magneto-Rheological Fluid (MRF) Boring Bar exhibit some advantages over typical ER materials. Compared to ER fluids [23], which have high working voltages (2–5kV) and narrow working temperatures (10–70°C), the power (1–2A or 50W) and voltage (12–24V) requirements for MR fluid activation are relatively small, and the working temperatures (−40-150°C) of MR fluid are relatively broadened. So MR fluids are more practical and suitable for machine tool applications. In addition, ER fluids are sensitive to impurities, which is not a problem for MR fluids [26].

In this study, an MR fluid boring bar-controlled surface quality improvement method is proposed. The synthesis of MR fluids is detailed first, and then the mechanics of chatter suppression using MR fluid boring bar is explained along with the design and fabrication of the MR fluid boring bar. Next, a finite element model of the MR fluid boring bar is established to investigate the strength of magnetic field at various locations of the boring bar for different current inputs. Finally, the surface roughness measurements are made on various materials with/without Magneto-rheological effect.

SYNTHESIS OF MR FLUIDS:

Magneto-rheological(MR) fluids are the suspensions of micron sized, magnetisable particles (iron, iron oxide, iron nitride, iron carbide, carbonyl iron, chromium dioxide, low-carbon steel, silicon steel, nickel, cobalt, and combinations thereof) in an appropriate carrier liquid (non-magnetisable) such as mineral oil, synthetic oil, water or ethylene glycol. The carrier liquid serves as a dispersed medium and ensures the homogeneity of particles in the fluid. A typical MR fluid consists of 20–40 percent by volume of relatively pure, 3-10 micron diameter iron particles, suspended in a carrier liquid. They are field responsive in nature and the magneto-rheological response of these fluids lies in the fact that the polarization is induced in the suspended particles by the application of an external magnetic field. The concentration of these materials plays a vital role as the properties of the MR fluid depend on these concentrations. The properties are subject to change if different concentrations of carrier fluid, magnetic particles and additives are used. For the current study, two MR fluids were prepared using two different concentrations (by volume) of magnetic particles.

The first concentration of MR fluid incorporates 40% by volume of magnetic particles. These are carbon based iron particles and are called as carbonyl iron particles. They were mixed with the carrier fluid (Silicone oil) only and kept undisturbed for a period of five days to observe the gravitational settling. It was observed that the particles settled approximately 120ml in a period of 5 days from the total height of the fluid column. Figure 1 shows the gravitational settling of carbonyl iron particles.
Later, additives were added to the mixture of iron particles and carrier fluid. The gravitational settling in this case was observed to be less than the settling of particles without the additives. This decrease in the settling of iron particles depicts the importance of the additives in an MR fluid. The particles in the former case settled hard and were not easily re-dispersible when compared to the latter case. Hence, it can be said that the additives added to the MR fluid enhanced the lubricity and modified the viscosity. Figure 2 shows the synthesized MR fluid for 40% by volume concentration of iron particles inclusive of additives (MRF-1).

The second concentration of MR fluid incorporates 36% by volume of iron particles. As the gravitational settling was observed in the synthesis of the first fluid, the second MR fluid was synthesized by directly mixing the carrier fluid and additives with the iron particles. Figure 3 shows the synthesized MR fluid pertaining to 36% by volume iron particles (MRF-2).
The MR fluids synthesized have different concentrations of iron particles. Depending upon the apparatus available to measure the concentration of iron particles, 100ml of particles were measured while synthesizing both fluids and appropriate concentration of carrier fluid was added, to both, in order to balance the ratio of 40-60 for the first MR fluid and 36-64 for the second MR fluid. Here comes the concept of porosity into picture. The MR fluid with high concentration of iron particles, i.e. 40%, is more porous than the MR fluid with low concentration of iron particles, i.e. 36%. This can be observed from figures 3&4 where the final quantity of the mixture of MR fluid is different in both cases. The quantity of the MR fluid with 40% by volume of iron particles is less when compared to the quantity of the MR fluid with 36% by volume of iron particles even though the total quantity of the concentration of iron particles and carrier fluid was same. This is due to the presence of large number of pores for MR fluid with 40% by volume of iron particles.

**MECHANICS OF CHATTER SUPPRESSION**

Most chatter is what is termed regenerative chatter, which is usually caused by instability of the cutting process in combination with the mechanical structure of machining system. The frequency of regenerative chatter is close to the natural frequency of the machine tool. The tool tip displacement $Y$ is generated by the dynamic cutting force $F$ applied at the tool tip. The dynamic behavior of the mechanical structures is expressed by the dynamic flexibility $R$. The transient variation of chip thickness $h$ is the difference between $Y$ and the wavy surface $X$ generated in the previous cutting pass. In an unstable cutting process, $F$ will increase gradually. In boring, $T$ is the period of spindle revolution, $K_d$ is the cutting force coefficient (relating the cutting force to chip area), and $b$ is the cutting width.
The mechanical structure of a boring system can be simplified to a single degree of freedom system modeled by a combination of equivalent mass \((m)\), spring \((k)\), and damping \((c)\) elements. The chatter frequency of the cutting process \(\omega_c\) is \[27\]:

\[
\omega_c = \sqrt{\omega_n^2 + \frac{k_d b(1-\cos\emptyset)}{m}} 
\]  

(1)

where \(\omega_n\) is the natural frequency of the mechanical structure of the boring system.

When chatter occurs, the vibration frequency \(\omega\) is equal to \(\omega_c\), and the cutting process is located in the unstable region. At this moment, if \(\omega_n\) is changed by adjusting structural stiffness, \(\omega\) will remain equal to \(\omega_c\) for a short period of time. The cutting process will shift to the stable region because the vibration frequency is not equal to the resonant frequency of the system. Once in the stable region, the amplitude of vibration decays rapidly, and chatter is suppressed. However, the vibration frequency may shift to a new unstable resonant frequency during cutting, meaning the chatter could occur again.

If \(\omega_n\) is changed continuously using MR fluid control, chatter can be suppressed. This concept is similar to changing spindle speed to suppress chatter. When chatter occurs, the cutting process will be in the unstable region. At this moment, if \(\omega_n\) can be increased by increasing the stiffness of the MR fluid-controlled boring bar, according to Eq. (1), the chatter frequency \(\omega_c\) will increase and shift to the stable region. The cutting process is then in the stable region, and chatter is suppressed.

As the cutting process continues, it may again shift into the unstable region. When that happens, \(\omega_n\) can be reduced by decreasing the stiffness of the MR fluid-controlled boring bar. Just as when \(\omega_n\) is increased, the cutting process is then back within the stable region. Thus, conditions promoting regenerative chatter can be dealt with by either increasing or decreasing \(\omega_n\).

According to above theoretical analysis, as long as an innovative stiffness-tunable boring bar based on MR fluid can be developed, the chatter can be suppressed in boring process.

For the chatter suppression method proposed in this paper, we just need to input a 1–5 Hz periodical square wave current to MR fluid controlled boring bar, so the response time of MR fluid is quick enough for the natural frequency adjustment and control in this research.
By surrounding the base of the boring bar with MR fluid, as shown in Figure 4, the stiffness and natural frequency of the boring bar can be continuously varied by changing the intensity of the magnetic field passing through the MR fluid. The boring bar assembly in Figure 4 consists of the MR fluid, a cylinder, a non-magnetic sleeve, an electromagnet, and a boring bar with two shoulders, marked as S1 and S2. To fabricate this boring bar assembly, the electromagnet is first embedded between the two shoulders of the boring bar and coated with ethoxyline resin. The non-magnetic sleeve and cylinder are then assembled. The MR fluid is poured into the annular cavity and then sealed in by a cap and O-rings. The thickness of the MR fluid layer in the annular cavity is about 1.0mm. The diameter of the boring bar is 20mm, the ratio of length and diameter is 6, and the length of the fixed portion is 160mm.

**FE ANALYSIS OF MAGNETIC SYSTEM**

The magnetic system for the MR fluid boring bar is important for energy transformation efficiency, as well as the chatter suppression capability of the system. FE analysis was applied to analyze and design the magnetic field. The boring bar and cylinder are made of low-carbon steel with a magnetic conductivity of 1000H/m. The MR fluid is MRF-132DG, produced by the LORD Corporation, USA. The magnetic conductivity of this MR fluid is 15H/m. An axi-symmetric FE model of the magnetic system was used to analyze the MR fluid boring bar shown in Figure 5.

The electromagnet shown in Figure 7 of the magnetic system consists of 200 turns, 24AWG coil wire and was energized by 0.5-2.0A DC. The direction of magnetic flux lines is shown in Figure 4 by the arrow lines. The geometry of the boring bar components was designed with the goals that the magnetic lines of flux are perpendicular to the thin layer of MR fluid in shaft shoulders S1 and S2, and most magnetic lines of flux can go through two shoulders, thus enabling better actuation of the MR fluid.
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Figure 5. FE model and results of the magnetic system for a Magneto-rheological Fluid Boring Bar (a) Magnetic flux density at 0.5A input current (b) Magnetic flux density at 1.0A input current (c) Magnetic flux density at 1.5A input current (d) Magnetic flux density at 2.0A input current.

Experimental Setup: It consists of a Magneto-rheological fluid (MRF) boring bar (Figure 6) installed on a lathe machine as shown in Figure 8. A regulated power supply shown in Figure 9 was used to supply variable current to the boring bar at constant voltage. A surface roughness tester shown in Figure 10 was used to measure the surface roughness values of all the test specimens (Figure 11).

Figure 6. Magneto-rheological Fluid Boring Bar

Figure 7. Electro-magnet
Figure 8. MRF Boring Bar installed on Lathe

Figure 9. Surface Roughness Tester

Figure 10. Regulated Power Supply

Figure 11. All Test Specimens
RESULTS & DISCUSSIONS
The experiments were conducted on various materials at two spindle speeds i.e. 775 rpm and 1020 rpm with two MR Fluids i.e. MRF-I (40% magnetisable particles by volume) and MRF-II (36% magnetisable particles by volume).

I. Bronze

![Figure 12. Surface Roughness of Bronze at 775 RPM](image)

![Figure 13. Surface Roughness of Bronze at 1020 RPM](image)

**Table.1**: Surface roughness values of Bronze

<table>
<thead>
<tr>
<th>BRONZE</th>
<th>775 RPM</th>
<th>1020 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT(A)</td>
<td>MRF-I</td>
<td>MRF-II</td>
</tr>
<tr>
<td>0</td>
<td>2.39</td>
<td>2.35</td>
</tr>
<tr>
<td>1</td>
<td>2.19</td>
<td>2.14</td>
</tr>
<tr>
<td>1.5</td>
<td>1.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2</td>
<td>2.33</td>
<td>2.90</td>
</tr>
</tbody>
</table>
The least Surface roughness value for MRF-I at 775 rpm and 1020 rpm was recorded at current of 1.5A and the highest values at 0A (Table.1). The highest Surface roughness value for MRF-II at 775 rpm was recorded at current of 2A and for 1020 rpm at 0A and least Surface roughness value for 775 rpm is at 1A and for 1020 rpm at 2A (Table.1).

II. Aluminium

![Figure 15. Surface Roughness of Aluminium at 775 RPM](image)

![Figure 16. Surface Roughness of Aluminium at 1020 RPM](image)
Table.2: Surface roughness values of Aluminium

<table>
<thead>
<tr>
<th>ALUMINIUM</th>
<th>775 RPM</th>
<th>1020 RPM</th>
</tr>
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<tbody>
<tr>
<td>CURRENT(A)</td>
<td>MRF-I</td>
<td>MRF-II</td>
</tr>
<tr>
<td>0</td>
<td>3.04</td>
<td>5.40</td>
</tr>
<tr>
<td>1</td>
<td>1.72</td>
<td>4.48</td>
</tr>
<tr>
<td>1.5</td>
<td>4.58</td>
<td>2.07</td>
</tr>
<tr>
<td>2</td>
<td>6.00</td>
<td>3.31</td>
</tr>
</tbody>
</table>

**Figure 17.** Surface roughness v/s input current

The least surface roughness value for MRF-I at 775 rpm is recorded for current of 1A and at 1020 rpm 1.5A and the highest values at 775 rpm at 2A and for 1020 rpm at 0A. The least surface roughness value for MRF-II at 775 rpm and 1020 rpm is recorded for current of 1.5A and the highest value at 775 rpm at 0A and for 1020 rpm at 1A(Table.2).

**III. Brass**

**Figure 18.** Surface Roughness of Brass at 775 RPM
Table 3: Surface roughness values of Brass

<table>
<thead>
<tr>
<th>BRASS</th>
<th>775 RPM</th>
<th>1020 RPM</th>
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</thead>
<tbody>
<tr>
<td>CURRENT (A)</td>
<td>MRF-I</td>
<td>MRF-II</td>
</tr>
<tr>
<td>0</td>
<td>1.74</td>
<td>2.11</td>
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<tr>
<td>1</td>
<td>1.38</td>
<td>0.52</td>
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<tr>
<td>1.5</td>
<td>0.56</td>
<td>1.56</td>
</tr>
<tr>
<td>2</td>
<td>2.49</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Figure 19. Surface Roughness of Brass at 1020 RPM

The least surface roughness value for MRF-I at 775 rpm and 1020 rpm is recorded for current of 1.5A and the highest values at 775 rpm at 2A and for 1020 rpm at 1A. The least surface roughness value for MRF-II at 775 rpm and 1020 rpm is recorded for current of 1A and the highest value at 775 rpm and 1020 rpm at 0A (Table 3).
IV. Copper

Figure 21. Surface Roughness of Copper at 775 RPM

Figure 22. Surface Roughness of Copper at 1020 RPM

Table 4: Surface roughness values of Copper

<table>
<thead>
<tr>
<th>COPPER</th>
<th>775 RPM</th>
<th>1020 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT(A)</td>
<td>MRF-I</td>
<td>MRF-II</td>
</tr>
<tr>
<td>0</td>
<td>2.40</td>
<td>2.69</td>
</tr>
<tr>
<td>1</td>
<td>1.96</td>
<td>2.45</td>
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<td>1.5</td>
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</tr>
<tr>
<td>2</td>
<td>3.73</td>
<td>3.90</td>
</tr>
</tbody>
</table>
The least surface roughness value for MRF-I at 775 rpm is recorded for current of 1A and 1020 rpm at 1.5A and the highest values at 775 rpm and 1020 rpm at 2A. The least surface roughness value for MRF-II at 775 rpm is recorded for current of 1.5A and for 1020 rpm at 1A and the highest value at 775 rpm at 2A and for 1020 rpm at 0A (Table.4).

**CONCLUSIONS**

A chatter suppression method based on a MR fluid boring bar was presented. Two different MR fluids with 40% and 36% of magnetisable particles are proposed. A Magneto-rheological Fluid Boring Bar is fabricated and experiments were conducted using the same. The magnetic system inside the boring bar was designed using the FE analysis. Fig. 5(a) to (d) shows that the magnetic flux density is maximum at thin layer of MR fluid and the core of the electromagnet. So the FE analysis of magnetic system for the MR fluid boring bar shows that the design of its magnetic system is reasonable.

It is observed that the optimum Surface roughness value of 2.25µm for Bronze is obtained at an input current of 1.2A for both MRF-I and MRF-II at both the speeds (Figure.14). For Aluminum the optimum Surface roughness value of 3µm is observed at a current of 1.3A for both the fluids (Figure.17). The optimum Surface roughness value of around 1.5µm for Brass is recorded at two different currents i.e. at 1.4A and 1.8A (Figure.20). For Copper the optimum Surface roughness value of 2.25µm is observed at a current of 1.3A for both fluids (Figure.23).
REFERENCES


