Experimental studies on the ultra-precision finishing of cylindrical surfaces using magnetorheological finishing process

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In modern manufacturing and assemblies, high-dimensional accuracy and fine surface finishing play an important role. One of the most promising methods of fabricating such high-precision parts is magnetorheological finishing process. In cylindrical components grinding, the external surface is ground and by obtaining a high-precision finished surface these components will perform better in mechanical systems. This process is not readily applicable to magnetizable materials, if a high-magnetic field is used. This is due to the attraction of workpiece by magnetic force and preventing it to rotate. In this study, the main mechanism is responsible for the decrease of Ra on external surface of cylindrical workpieces made of non-magnetizable materials, and a new method based on MRF process is examined. The examined specimens in this study are made of aluminum (Al), it is known as a kind of non-magnetizable, soft, and lightweight materials. The apparatus that used for this experiment includes two main motions. The first one is using a rectilinear alternating motion to improve processing conditions, and the second one is specimen’s rotational motion. The experiments of this study show the applicability of this method for finishing cylindrical surfaces made of Al.

Keywords: magnetorheological fluid finishing (MR fluid finishing); aluminum; cylindrical surfaces; non-magnetizable materials

1. Introduction

Magnetorheological finishing (MRF) is a deterministic polishing technology for ultra-fine surfaces. Researchers focused their efforts on magnetorheological (MR) theory, MR fluid, and the development of MRF system. Considerable research efforts have been done on the development of ultra-fine finishing processes for complex 3D structures. Non-traditional manufacturing processes like ion-milling (Mitsuishi, Shimojo, & Furuya, 2006) and electro-discharge machining (EDM) (Abbas, Solomon, & Bahari, 2007; Fleischer, Masuzawa, Schmidt, & Knoll, 2004) are frequently used as the primary process for shaping and/or manufacturing these components. Thus, the middle products obtained frequently require ultra-fine surface quality (a few to tens of nanometers in surface and/or shape accuracy), thereby creating a critical demand for efficient surface finishing processes.

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Kim, Lee, and Min (2004) performed preliminary experiments for the finishing of silicon-based structures with a group of micro-sized straight channels, and obtained an optimized procedure, together with associated experimental conditions. During MR finishing, they found that the average channel height decreased by 2–3 mm with the formation of slight rounding at the edges (or corners).

To predict the shape and size of the influence function that contains the information about the material removal characteristic of the polishing tool on such surfaces, they performed a mathematical modeling study that takes into account process parameters such as the wheel speed, the magnetic field strength, and the fluid flow rate, and they experimentally verified the effectiveness of their model (Schinhaerl et al., 2008a, 2008b). Currently, two types of MR fluid are widely used in industrial settings. The first one is made of micron-sized CeO2 powder suspended in an aqueous medium of magnetic CI powder, and the second one employs diamond powder as the polishing abrasive (Lee, Hwang, Valente, Oliveira, & Dornfeld, 2006; Zantye, Kumar, & Sikder 2004). The second type of abrasives is examined during the tests.

In this study, experiments are carried out to introduce a new method for high-precision finishing of non-magnetizable cylindrical components through MRF. Experimental results showed the efficiency of the proposed method. The remainder of the paper is structured as follows. Sections 2 and 3 present the fundamentals on this MR finishing process, and the experimental setup, respectively. Section 4 focuses on the experiment procedure: firstly using variable workpiece speed, secondly testing variable process time, and thirdly evaluating the fast rectilinear alternating motion (RAM) effects in finishing process. Concluding remarks are presented at the end.

2. Fundamentals on MR finishing process

With application of a magnetic field, diamond particles form a chain-like columnar structure. It is well known that the chains of MR particles are aligned along the lines of magnetic force (Jha & Jain, 2004). In case that the workpiece surface has relative motions with respect to these chains, wear occurs on the surface.

As shown in Figure 1, it is believed that when the workpiece surface is rubbed by MR particle chains, the asperities on the surface are abraded. This is due to plastic deformation at the tips of the asperities caused by the high-stress concentration (Archad, 1953). Figure 2 depicts an actual surface profile of a specimen. The left-hand half is the portion of unpolished surface, whereas the right-hand half is that of polished surface.

Figure 1. Plausible wear mechanism in MR finishing process.
It is observed that the asperities on the right-hand half have been selectively worn away.

3. Experimental setup

Finishing experiments were performed using an MR finishing apparatus approximately similar to a wheel-type one, but with some differences. As shown in Figure 3, this equipment is primarily composed of a moving plate that can provide a controlled...
swinging motion in the direction of \( Y \)-axis, a spindle which is able to rotate at a controlled speed (the specimen is held on the spindle which has been connected to a servomotor) and a magnetic field that can generate a magnetic force to absorb abrasive particles to itself. The magnetic field strength is given indirectly by the inductor current and has, therefore, unit of amps. In this study, the magnetic field strength is 9 amps.

The MR fluid used in this study was water-based suspension of micron-sized diamond particles which are nearly spherical and have diameters ranging from 10 to 20 \( \mu m \). The specimens were made of Al, a type of lightweight and non-magnetizable materials, in a cylindrical shape with an outer diameter of 40 mm, inner diameter of 10 mm, and height of 15 mm which is shown in Figure 4(a). It is connected to a servomotor through a spindle (see S1 in Figure 4(b)).

In this setup, when the MR fluid is added in the moving plates’ case, after activation of magnetic field, the abrasive particles are absorbed immediately by magnetic force and fill the gap distance by settling in the magnetic field. The magnetic field has a rectangular area of 70 × 20 mm on the moving plate. Then the spindle and moving plate start to rotate and move, respectively, and through this process the workpiece is finished. The moving plate is rigidly connected to an arm that can make a controlled swinging motion (in the direction of \( Y \)-axis), using a crank mechanism driven by another servomotor (S2 in Figure 4(b)), and employs a case because the workpiece is submerged in the MR fluid. In addition, a tank is used in this setup that pump the water into the case continuously, the removed materials in external fluid are filtered and it returns to the tank again. The primary reason for the swinging motion of the moving plate is to integrate the formation of particles chains. The vertical position (gap distance) of this system can be adjusted manually.

4. Experimental procedure

Three sets of experiments were performed to examine the feasibility of using this type of MR equipment to finish the surface of Al: the first set determines the best specimen rotational speed for this process, the second one investigates the effects of process time, and the third one indicates the effects of using a fast RAM on the surface roughness (Ra) reduction. In all of experiments, the gap distance between specimen and the surface of magnetic field was 5 mm. As it is shown in Figure 5(a) and (b), when the magnetic field is activated the abrasive particles in MR fluid are settled in it and fill the gap distance.

As it mentioned earlier, the first set of experiments tries to define the best rotational speed for specimen in this type of process. It was performed by varying rotational speed.
from 250 to 1000 rpm in increments of 250 rpm, and each one was run for 20 min, which was determined from an experiment performed to identify the convergence time for surface roughness. It can be seen clearly in Figure 6, since the surface roughness (Ra) of the original pre-polished surface was 170 nm, the Ra values of the finished surface could be higher in some rotational speeds. To explain more, the material removal rate and surface roughness tend to increase, as the specimen rotational speed enhanced to around 500 rpm, and decreased subsequently thereafter. This is a commonly observed trend in MR finishing processes. The first set of experiments showed that this finishing process yields a considerable improvement in surface quality at the rotational speed of 1000 rpm because the Ra value was decreased about 40 nm compare with the original surface roughness. By showing that this rotational speed is capable of improving the surface quality better than other speeds, the rest of experiments were performed at this speed.

It can be inferred that during the finishing process, diamond particles in the MR fluid are brought into direct contact with the specimen surface via a definite pressure, and they trim out the local asperity peaks by applying a shear stress higher than their yield stress value.

The second set of experiments was performed by considering the effects of process time on surface roughness (Ra) reduction; it is processed with the conditions that follow: the gap distance is 5 mm and the rotational speed is 1000 rpm. In the previous stage, each experiment was run just for 20 min, but in this stage different finishing times were examined in order to determine the most suitable time and proving the effects of this parameter on this type of MR finishing. The experimented finishing times are started from 20 min up to 100 min.

Figure 7 depicts the variation of the surface roughness (Ra) with finishing time measured at every 10 min during MR finishing. As shown in this figure, it can be seen that the surface roughness (Ra) of the specimen is getting decreased gradually and reaches to the limiting value of 42 nm after about 90 min, and thereafter no considerable changes happened to the reduction of Ra value. The main reason may be due to the fact that as the finishing time goes over 90 min, the abrasive particles lose their capability of abrasion because of particles fatigue.

The last experiments in this study were performed to investigate the properties of using a fast RAM. It was processed with the following conditions: the specimen rotational speed is increased from 250 to 1000 rpm in increments of 250 rpm, the initial

![Figure 5. Particles position: (a) before activation of magnetic field and (b) after activation of magnetic field.](image)
mean surface roughness is 200 nm, the processing time for each run is fixed at 20 min, and the mean speed of moving plate (magnetic field holder) when RAM is applied is 0.5 m/s. Figure 8 compares the Ra value with and without a fast RAM, as it is obvious the surface roughness decreases with a constant value until the rotational speed reaches 250 rpm and then increases sharply up to 500 rpm. When the rotational speed is greater
than 500 rpm, the surface roughness decreases with rotational speed, and the Ra value reaches to its minimum at the speed of 1000 rpm. Results are listed in Table 1.

The speed of the superposed RAM given to the magnetic field is variable to examine the extent of the roughness improvement for Al. As might have been expected, the results listed in Table 1 indicate that increasing the relative speed between the magnetic field and the specimen improves the surface roughness by about 42.8%, and this is because the speed increase particularly accelerates the material removal on the asperity tips. Consequently, the finishing of soft materials, such as Al, could attain improved levels of performance from changes in the processing conditions, such as the superposition of a RAM.

### 5. Conclusion

A new machining process has been proposed in this work for finishing of cylindrical surfaces with the use of MR fluid, a smart finishing material generally used for ultrafine surface finishing. With the application of this procedure, it has been shown that MR finishing is particularly useful for the finishing of cylindrical surfaces made of Al. The specimen rotational speed and the process time were allowed to vary, and the changes in the surface roughness of specimen were investigated. It is shown that the Ra value of workpiece can be controlled with the two input control variables.

After performing two preliminary experiments, the following issues could be observed:

1. The surface roughness tended to increase with the rotational speed of the workpiece up to a certain critical value (500 rpm in this study), and to decrease for speeds beyond this value.
2. The surface roughness (Ra) is reduced regarding to process time. In other words, the Ra value will decrease by increasing the process time, and at a certain time (90 min in this study) it reaches to the limiting value and no significant change will happen thereafter.

Fast RAM was applied to improve the surface roughness of cylindrical workpieces to be finished with this process. It was proved that this motion plays a key role in reduction of Ra value, compare with the obtained values from an additional experiment performed independently.

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