AN ANALYSIS OF POLISHING FORCES IN MAGNETIC FIELD ASSISTED FINISHING

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INTRODUCTION
In magnetic field assisted finishing (MAF) a magnetic field is used to maneuver a flexible “magnetic brush” (composed of ferromagnetic particles and abrasives and formed by the magnetic fields) over the surface to be polished. The relative motion between the brush and the surface can be obtained either by rotating the brush, moving the sample, or both. The brush can consist of either: 1) sintered particles, where the ferromagnetic and abrasive particles (e.g., SiC, Al₂O₃, CBN, or diamond) are sintered together to form a ferromagnetic conglomerate; or 2) separate abrasive and ferromagnetic particles. For the latter case, the abrasives are held between and within the magnetic chains (brush) which are formed. A lubricant can also be used to aid in holding the abrasive particles within the flexible brush. Figure 1 provides a schematic of the material removal process.

FIGURE 1. MAF process.

In this study, the polishing forces during magnetic field assisted polishing were examined. The measured forces were divided into forces due to polishing effects and forces due to magnetic effects. A method to identify and isolate the different elements of the force measurement was established. The effect of varying the iron particle size and the working gap on polishing forces and surface roughness was examined. A coherence scanning interferometer (CSI) was used to measure surface roughness. A surface roughness of 2-3 nm Sa was achieved under certain conditions.

EXPERIMENTAL SETUP
The experimental setup consisted of mounting a permanent neodymium magnet in a fixture held in the spindle of a CNC milling machine. The sample was mounted on a ferromagnetic mount which completed the magnetic circuit and strengthened the magnetic field in the gap between the magnet and the sample. This increased the forces on the iron particles of the slurry. The sample was glued to the sample mount using an epoxy resin. The sample-sample mount combination was fixed on a 3D force sensor (Kistler 9256 C1). Each polishing trial consisted of approaching the sample in the normal direction to capture all the magnetic effects. The magnet was then rotated and translated for a fixed period before retracting back away from the sample.

Polishing Forces
The MAF forces can be divided into two categories: 1) magnetic effects; and 2) interactions between the brush and sample. When studying the forces for different polishing conditions, it is important to accurately separate the two categories. The magnetic forces exist mainly due to magnetic interactions between the permanent magnet, the ferromagnetic mount, the ferromagnetic slurry and any magnetism the sample may exhibit. Each of these effects were individually identified using a series of tests. Once the cumulative magnetic effects were evaluated, a reference was computed with respect to which the polishing forces can be measured.

The magnetic forces exist mainly in the normal direction along the axis of the magnet. The
symmetry that exists in the two orthogonal directions nullifies the magnetic effects and only polishing forces are observed. Tests were also conducted to evaluate the effect of translational velocity on lateral polishing forces.

**Surface Roughness**
The surface roughness was measured using the CSI at nine different locations on the sample after each polishing trial. Filtering was completed in accordance with ISO 4288. In order to correctly compare the performance of different polishing conditions it was necessary to establish a common starting roughness on all samples. The samples were initially polished using a nylon mesh pad to a consistent surface roughness of 70-90 nm Sa.

**RESULTS**

**Polishing Forces**
The normal force magnitude decreased slightly as the iron particle size increased. It is proposed that the smaller iron particles enabled the formation of a more even brush which caused a larger number of particles to be in contact with the sample. Therefore, although the smaller iron particles may experience smaller magnetic field forces individually, on the whole they apply more attractive force between the magnet and sample resulting in a higher normal force. This effect was also seen in the lateral force measurements. The normal polishing force exhibited a strong dependence on the working gap. This is because the flux density decreases as the working gap increases. The lateral forces were also inversely related to the working gap.

**Surface Roughness**
There is no material removal when the iron particle size (IPS) is smaller than the top width of the valley. As the IPS increases, the particles are prevented from entering the valleys and produce material removal at the peaks. It is also important to note that, although the entire brush might produce larger normal and lateral forces, each individual particle for the smaller sized iron particles exerts little force on the surface. Thus, the localized polishing force is higher when IPS is greater. This resulted in a faster improvement in surface roughness.

A combination of two factors dictates whether there is material removal: 1) the IPS should be larger than the top width of the valleys in the surface; and 2) the IPS must be large enough to impart sufficient force on the abrasive particles to cause material removal. The material removal rate and surface roughness improve significantly for larger IPS. The working gap (WG) was found to have little effect on polishing performance as long as the amount of slurry was maintained proportional to the WG.

**Surface Texture**
The direction of lay on the polished surface depends on the path of the slurry in contact with the surface. A direct correlation between the direction of the abrasive path and surface texture was observed.

**CONCLUSIONS**
A number of conclusions can be drawn based on the experimental results and analysis.

1. While measuring MAF polishing forces, it is necessary to isolate the magnetic field effects from the polishing effects.
2. The normal and lateral forces were found to have an inverse relationship with both IPS and WG.
3. The rate of improvement in surface roughness with polishing time depends on the IPS. If the particles are too small, there is little material removal even after polishing for prolonged periods of time. The rate of improvement in surface roughness is not sensitive to WG.
4. The translational velocity has almost no effect on the magnitude of lateral polishing force.
5. The lay of the polished surface is dictated by the path of the magnetic field and the direction of the abrasive particles.

**REFERENCES**