Magnetic Field Assisted Nanomachining of Ultraprecision Surfaces

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Abstract

The purpose of this study is to understand the nanoscale material deformation and removal mechanisms of magnetic field-assisted nanomachining, and to computationally model the mechanisms. To discover these mechanisms, specialized workpieces having a thin (tens of nanometers) soft metal (i.e. gold) coating on an ultrasmooth surface have been developed. The application of the magnetic field assisted nanomachining process to the soft metal layer reveals characteristic surface deformations from which the mechanisms may be deduced through careful analysis.

Motivation

Magnetic field-assisted nanomachining has been shown to be capable of machining high-aspect ratio features of MEMS devices. However, a lack of knowledge regarding the material removal mechanisms hinders control over the finished surface texture. This study could reveal the surface and sub-surface deformation mechanisms of brittle and ductile materials in the nanometer range. Such knowledge enables the polishing process as a viable surface finishing solution for high-aspect ratio components of microelectromechanical systems (MEMS) having surface roughness of < 1 nm.

Alternating magnetic field-assisted finishing (MAF)

Magnetic field-assisted finishing (MAF) employs a magnetic field having the strength and gradient to actuate a magnetic tool to machine a target surface. Since magnetic fields can permeate materials, it is used to machine conventionally inaccessible surfaces.

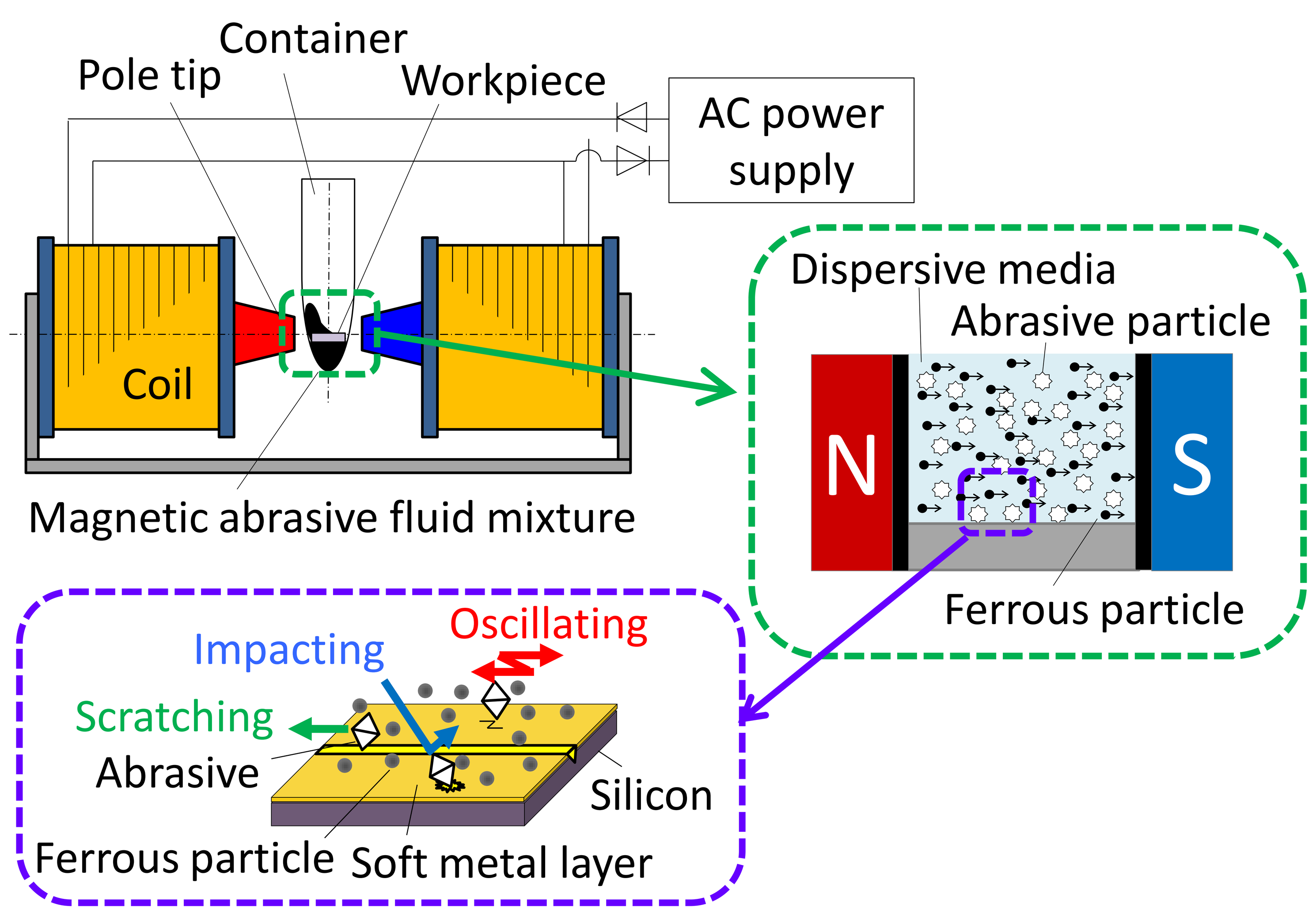


Fig. 1 Schematic of processing principle

An alternating MAF using a mixture of magnetic fluid (ferrofluid) and abrasive slurry as a polishing fluid was developed to achieve low-force/high-precision surface finishing. The alternating magnetic field actuates the mixture so that it flows in the direction of magnetic flux, machining the target surface (Fig. 1). The behavior of the abrasive particles is unknown.

Nanomachining with MAF

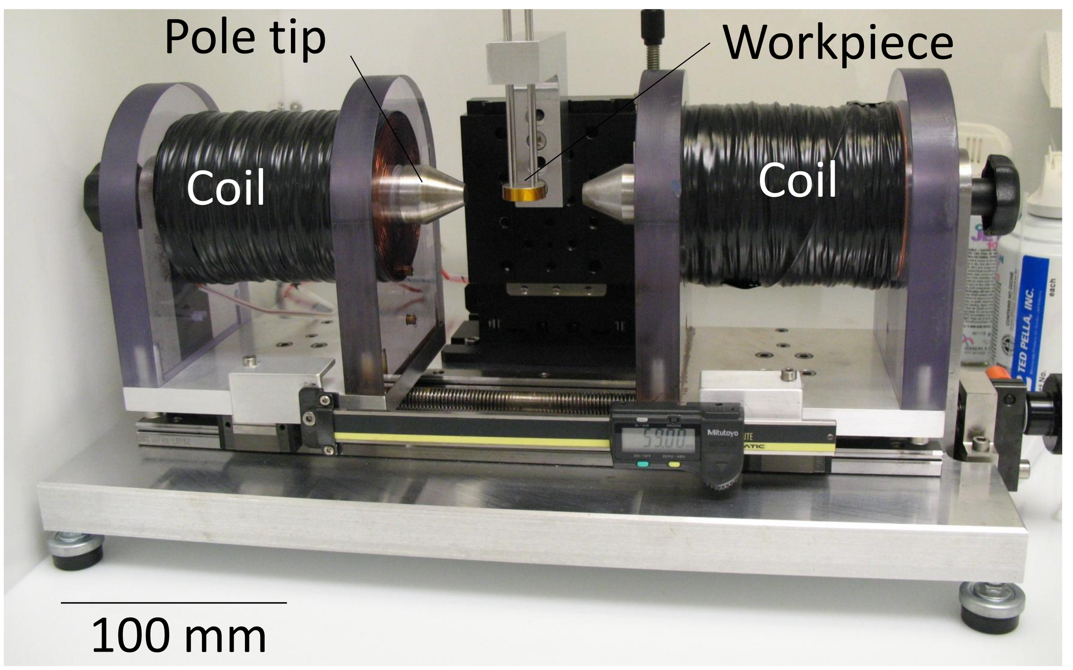
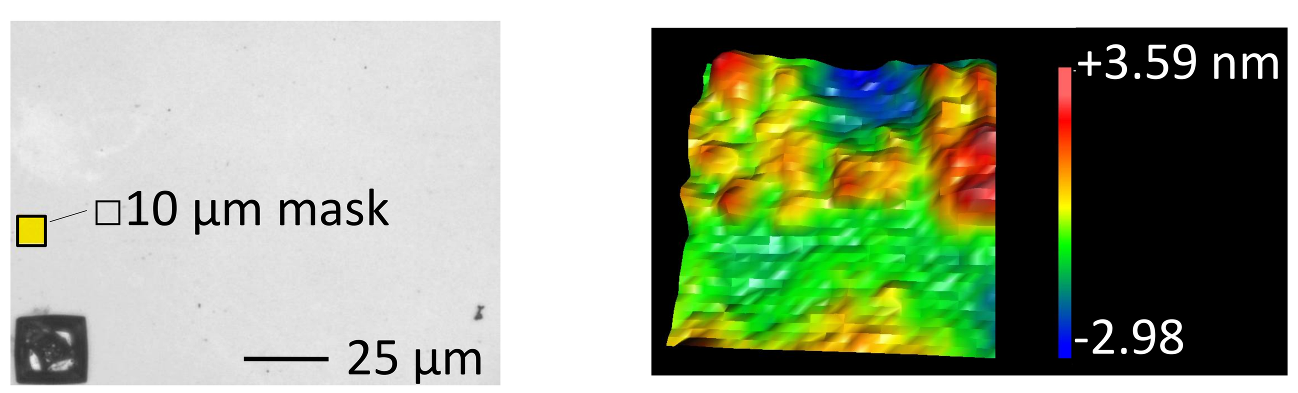


Fig. 2 Experimental setup

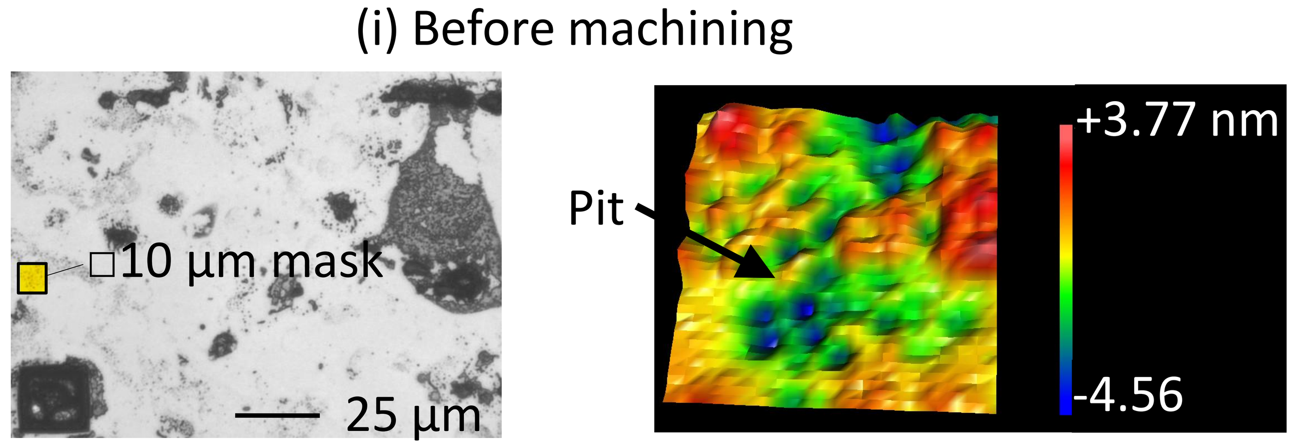
Table 1 Experimental Conditions

Workpiece	Si(100) 5.6×5×0.38 mm ~50 nm thick Au (sputtered)
Abrasive slurry	Universal-based polycrystalline diamond 0-0.5 µm diameter, 1 mL
Magnetic fluid	Water-based, anionic surfactant, 3.6 wt% Fe_3O_4, 1 mL
Pole-pole distance	22.5 mm
Alternating current	22 Hz, 1 A
Number of cycles	79,200 (1 hr)



(a) 176×132 µm area (b) □10 µm masked area

(i) Before machining



(a) 176×132 µm area (b) □10 µm masked area

(b) After machining

Fig 3. Surfaces measured by optical profiler

Understanding Nanoscale Material Removal Mechanisms

Nanoindentation studies aim to reveal the mechanism by which MAF achieves material removal. Nanoscale diamond abrasives impacting the surface in MAF is analogous to repeated loading with a nanoscale diamond tip.

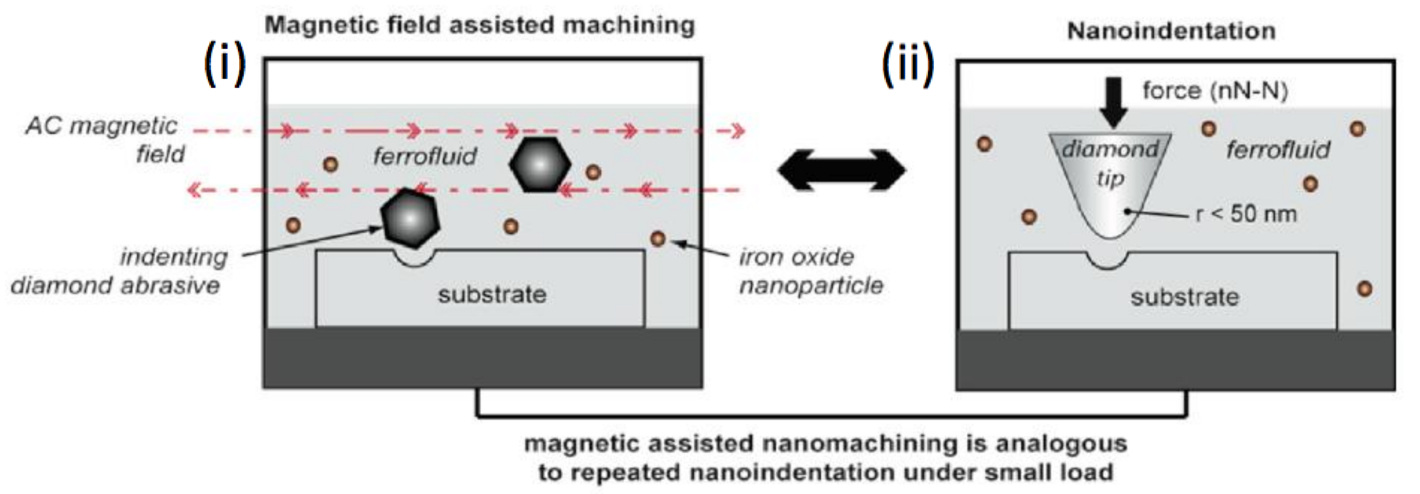


Fig. 4 Diagram showing analog of MAF to nanoindentation

One hypothesis is that repeated loading at low loads (<100 µN) creates dislocation nucleation and plastic zone growth that leads to fracture and material removal. We are investigating this hypothesis. To determine the threshold value for fracture in silicon, nanoindentation was performed using a diamond cube corner tip. Results show fracture above 200 µN.

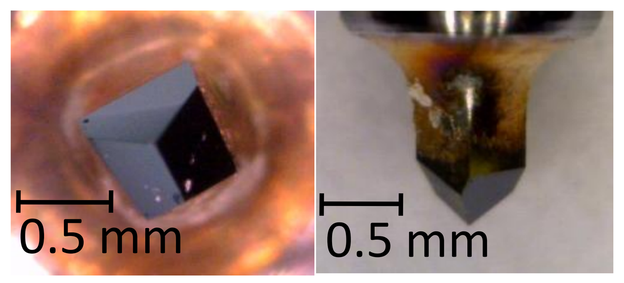


Fig. 5 Optical microscope image of diamond cube corner nanoindenter tip (tip radius ~ 40 nm)

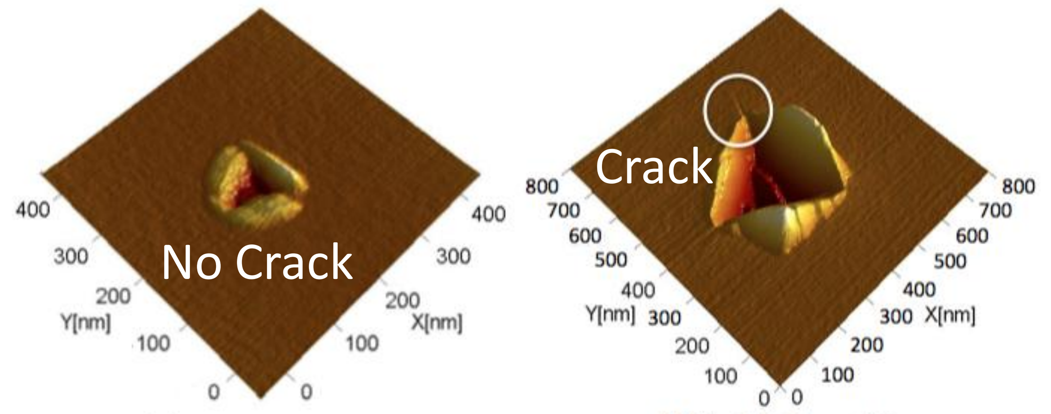


Fig. 6 AFM images of indents on Si(100).

Conclusions

1. A working experimental setup has been established.
2. Scanning white-light interferometer measurements indicated evidence of nanoscale surface deformation resulting from MAF.
3. Preliminary nanoindentation tests suggest a size effect with the surface cracking threshold force close to an order of magnitude lower than values found in previous studies .

Future work

A series of nanomachining trials are required to further study and characterize surface deformations. Moreover, a separate series of cyclic nanoindentation tests will be applied in order to reveal cracking at loads below the characteristic threshold force.

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