Magnetic Field-Assisted Nanomachining of Ultraprecision Surfaces

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PIs: Hitomi Yamaguchi Greenslet, Curtis R.Taylor Graduate Students: Raul Riveros, Jared Hann (University of Florida)

Abstract

The purpose of this study is to understand the nanoscale material deformation and removal mechanisms of magnetic field-assisted nanomachining. To discover these mechanisms, the process has been reconfigured to finish a flat workpiece. Nanomachining of the flat workpiece suggests that the surface was smoothed without disturbance to its overall geometry.

Motivation

Magnetic field-assisted nanomachining has been shown to be capable of machining high-aspect ratio features of microelectromechanical systems (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 solution to fabricate components with < 1 nm surface roughness.

Alternating magnetic field-assisted finishing (MAF)

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

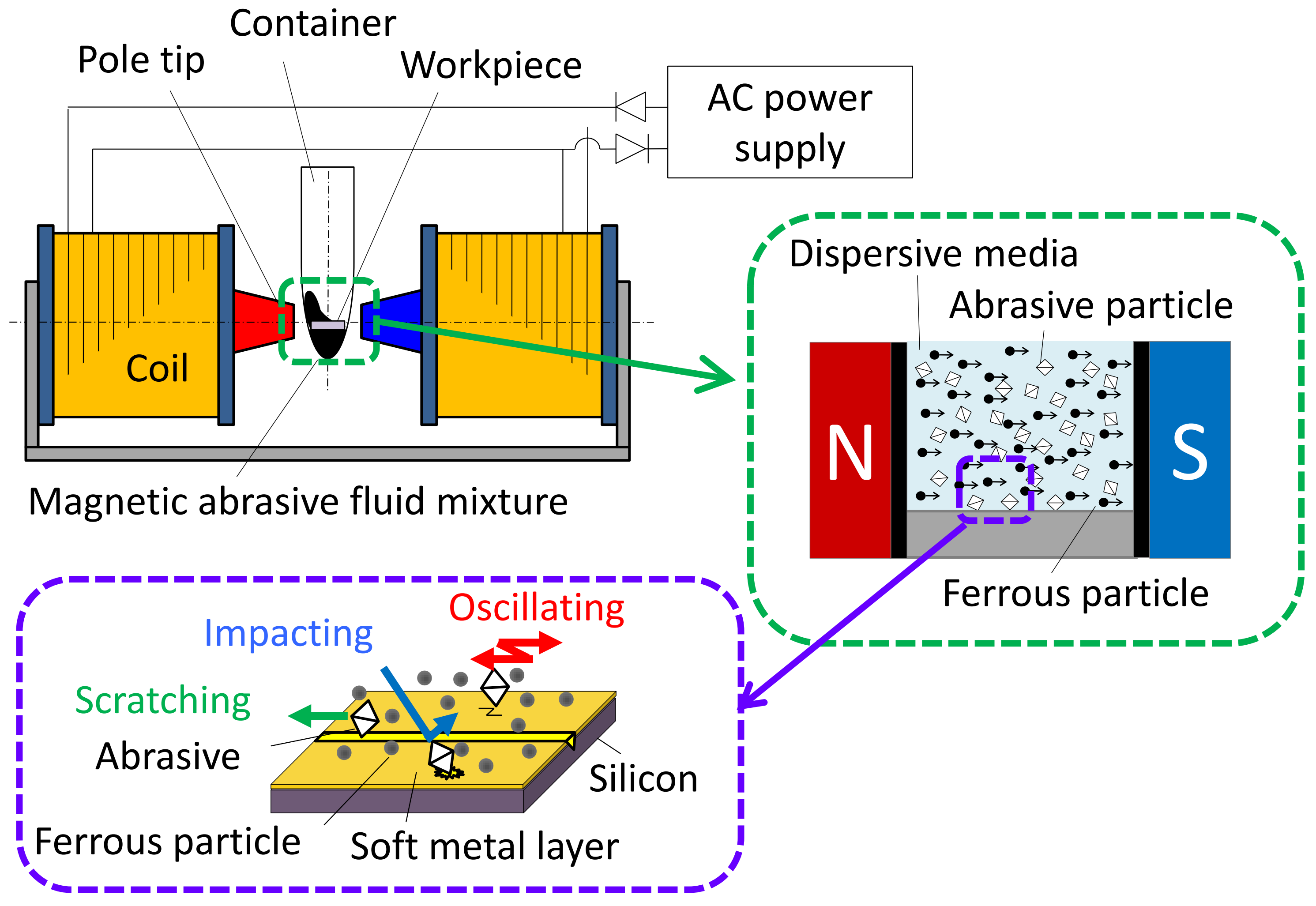

Fig. 1 Schematic of processing principle

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Nanomachining with MAF

An alternating MAF setup 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 currently unknown.**

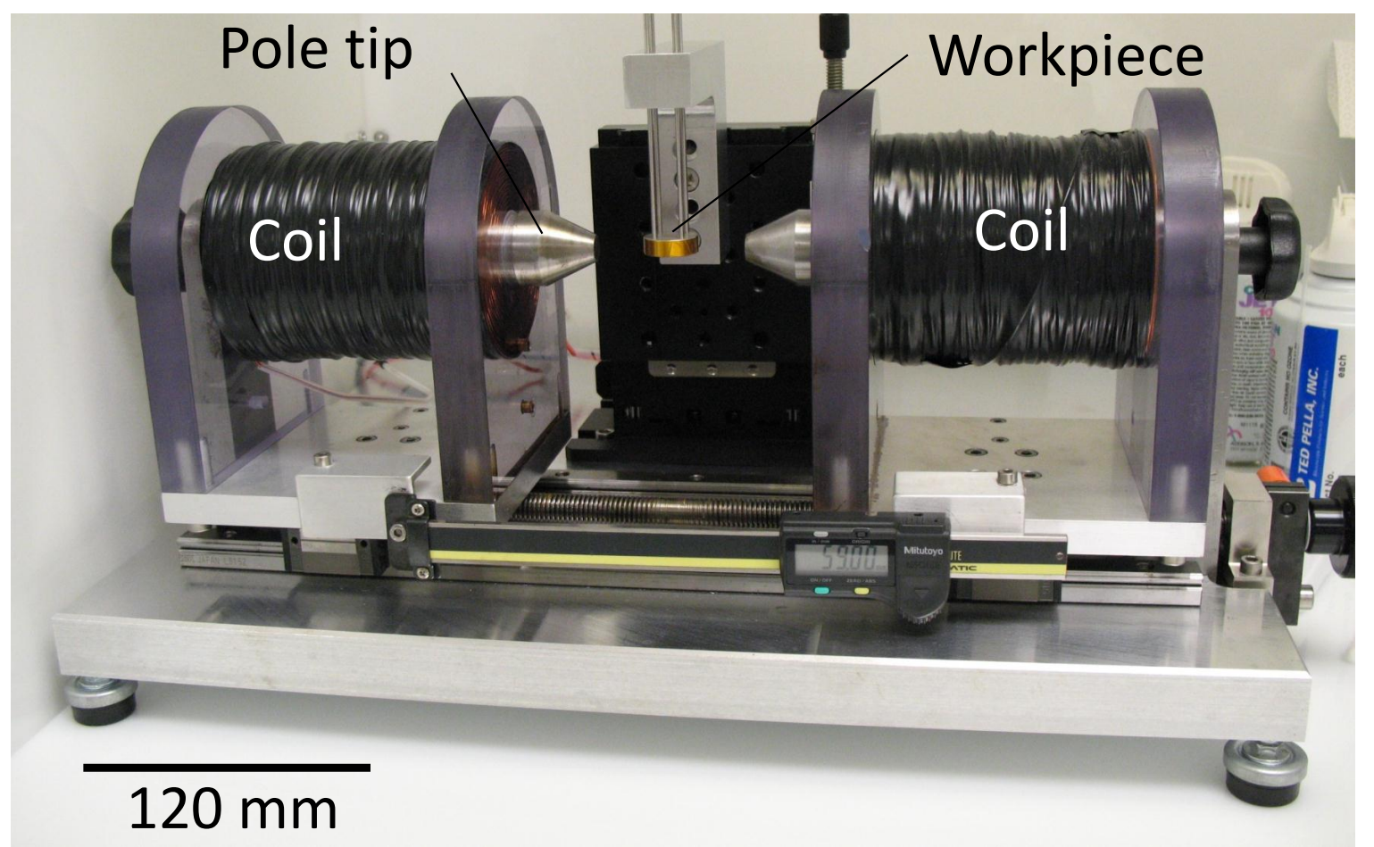


Fig. 2 Experimental setup

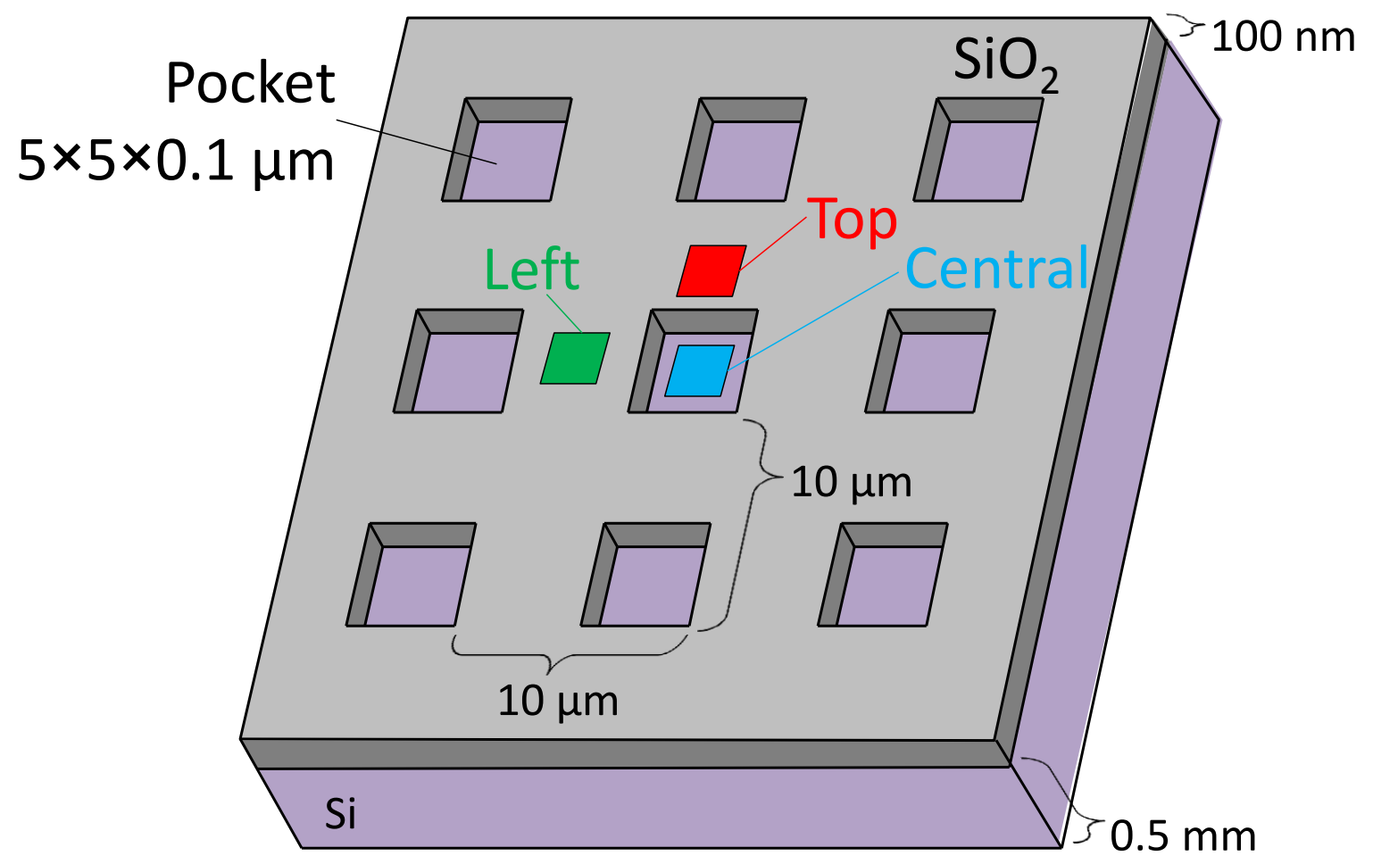
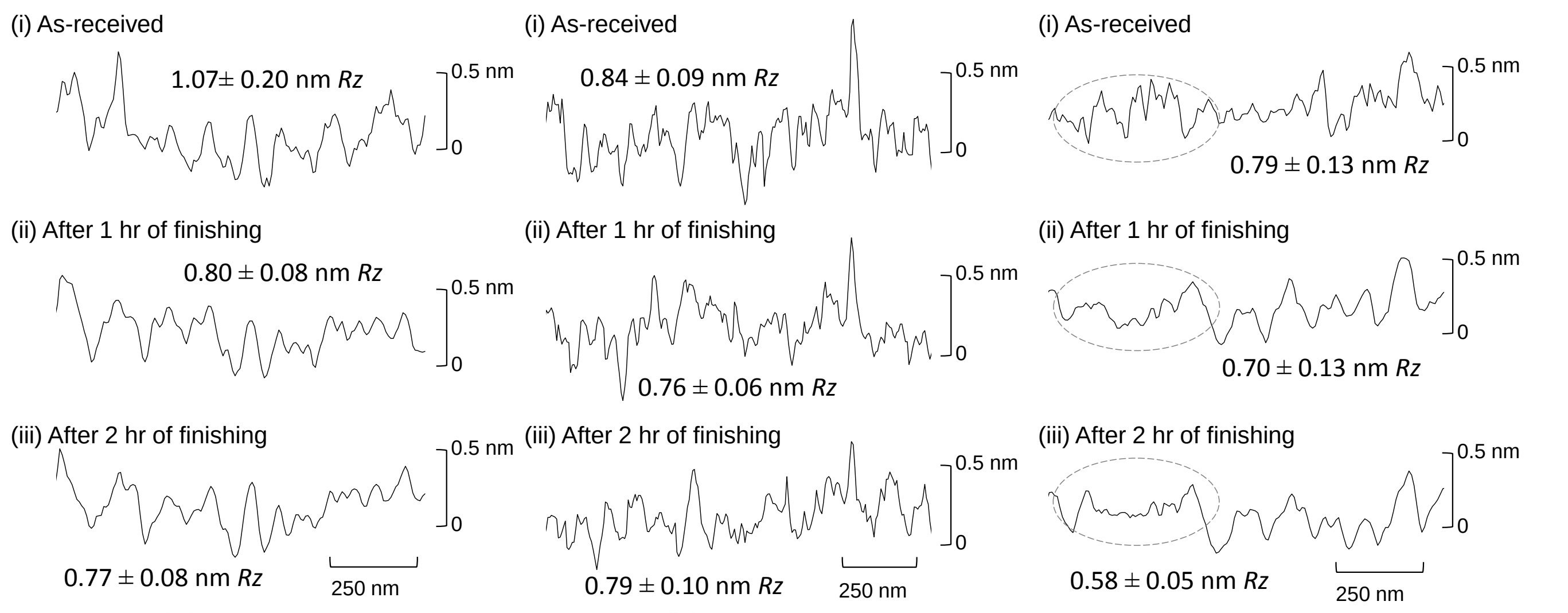


Fig. 3 Schematic of workpiece surface

Table 1 Experimental Conditions

Workpiece	5×5×0.5 mm silicon 100 nm-thick SiO2, patterned (see Fig. 3)
Abrasive slurry	Universal-based polycrystalline diamond 0–0.5 µm diameter, 1 mL
Magnetic fluid	Water-based, anionic surfactant 1.8 wt% Fe_3O_4, 1 mL
Pole-pole distance	22.5 mm
Alternating current	22 Hz, 1 A
Magnetic flux density	40.3 mT at center between pole tips
Finishing time	Two 1 hr phases (2 hr total)



(a) Top space (b) Left space (c) Central space

Fig. 5 Comparison of surface profiles in the central space with finishing time

Investigating the Material Removal Mechanism Using Nanoindentation

Nanoscale contact fracture was investigated as a possible material removal mechanism in MAF. Using a sharp cube corner (r = 32 nm) indenter in Si(100), the fracture threshold was found to be 280 – 290 µN. This is significantly higher than the load at which abrasives strike the substrate surface in MAF (<50 µN). However, it was hypothesized that the increased stress from adjacent and cyclic contacts in MAF may be capable of reducing the fracture threshold below 50 µN. To test this hypothesis, nanoindentation was performed as a function of load, indent separation, and load cycle.

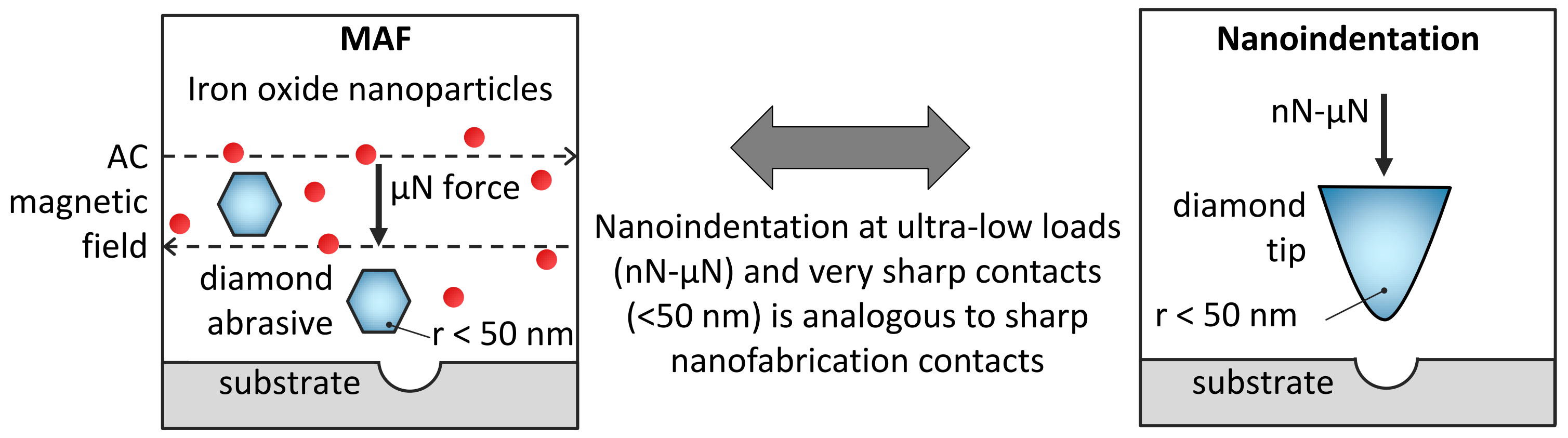


Fig. 7 Schematic showing that nanoindentation is analogous to, and therefore capable of simulating sharp nanoscale contacts in MAF

Nanoindentations were characterized using atomic force microscopy (AFM). Cyclic loaded indents resulted in greater plastic deformation and crack growth than single loaded indents (Figure 8(A)). Sequentially loaded adjacent indents resulted in greater plastic deformation and crack growth at small separations (Figure 8(B)) than isolated indents. However, neither adjacent indents nor cyclic loaded indents resulted in cracking below the fracture threshold load. **This indicates that fracture is not a material removal mechanism in MAF processes.**

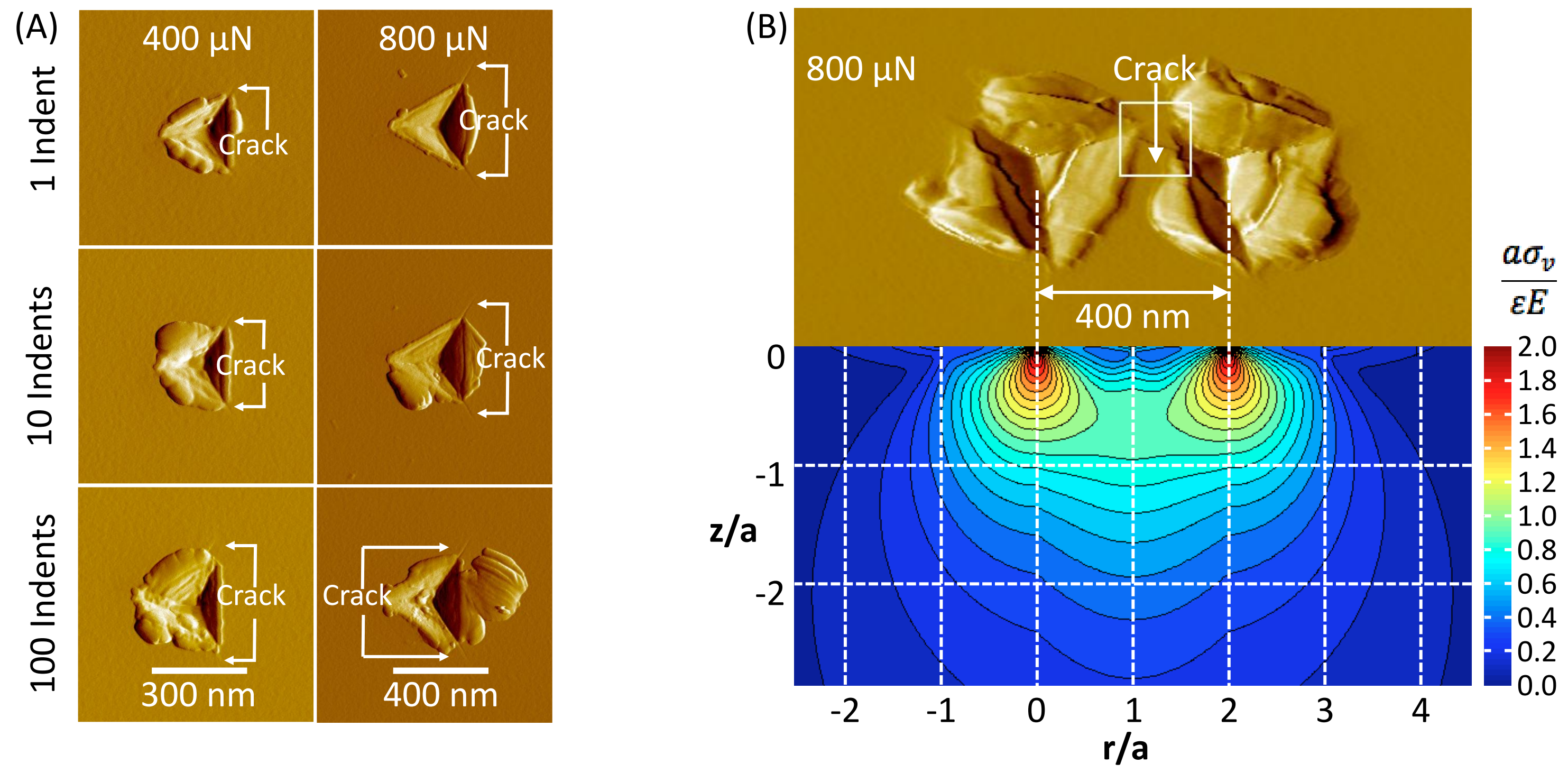


Fig. 8 AFM amplitude images of (A) cyclic loaded indents, showing an increase in deformation and cracking, and (B) adjacent indents separated by 2 indent radii, showing an intermediate crack, and the elastic Von mises stress contours normalized to indent radius (*a*), strain (*ε*), and elastic modulus (*E*).

Conclusions

1. The MAF process removed material from the workpiece surface at sub-nanometer increments rendering it capable of improving the surface roughness of features with little disturbance to their overall geometry.
2. Fracture was not observed below the threshold load (280-290 µN), single, adjacent, or cyclic loaded nanoindentations, indicating that fracture is not a valid material removal mechanism in MAF, where abrasives strike the surface with an estimated force of <100 µN.

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