Polishing Characteristics of YAG Ceramics using Magnetic Field-Assisted Finishing for High-Power Laser Applications

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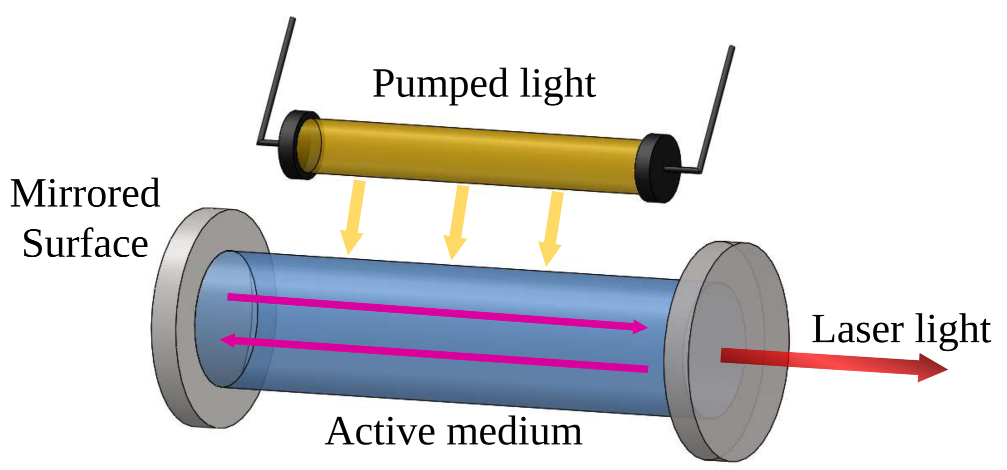
Abstract

Transparent yttrium-aluminum-garnet (YAG) ceramics have garnered an increased level of interest for high-power laser applications due to their ability to be manufactured in large sizes and doped in substantial concentrations. However, surface characteristics have a direct effect on the lasing ability of these materials, and a lack of a fundamental understanding of the polishing mechanisms of these ceramics remains a challenge to their utilization. The aim of this research is to clarify the polishing characteristics of YAG ceramics using magnetic field-assisted finishing (MAF). Through polishing with fine diamond abrasive, YAG ceramics can be reduced to sub-nanometer roughness despite inconsistent initial surface conditions. Uneven material removal between grains and increased material removal at grain boundaries becomes substantial when polishing with colloidal silica or when using iron particles below the average grain size. Reducing the sizes of both abrasive and iron particles can continue to improve the surface, however, it can potentially deteriorate localized defects if the iron particles can apply pressure onto the abrasive within the defects.

Motivation

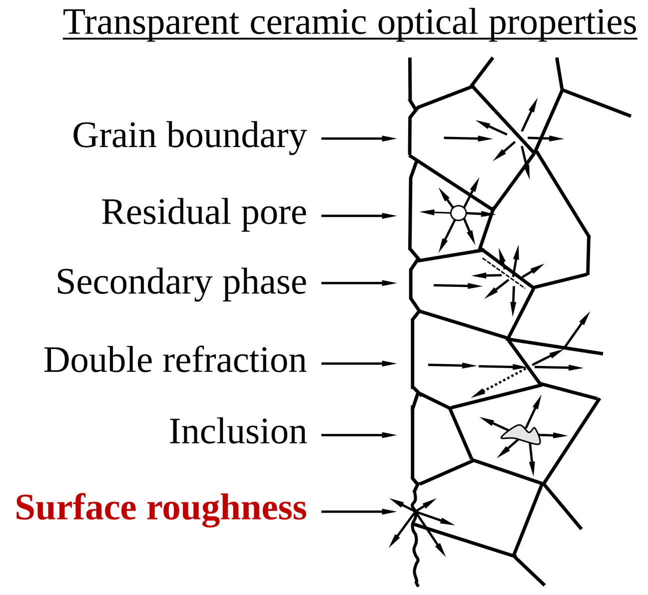
Due to their small footprint, enhanced mobility and excellent laser quality, solid state lasers have become the laser of choice for many industries including medical, manufacturing, defense, and communications.

Light Amplification by Stimulated Emission of Radiation

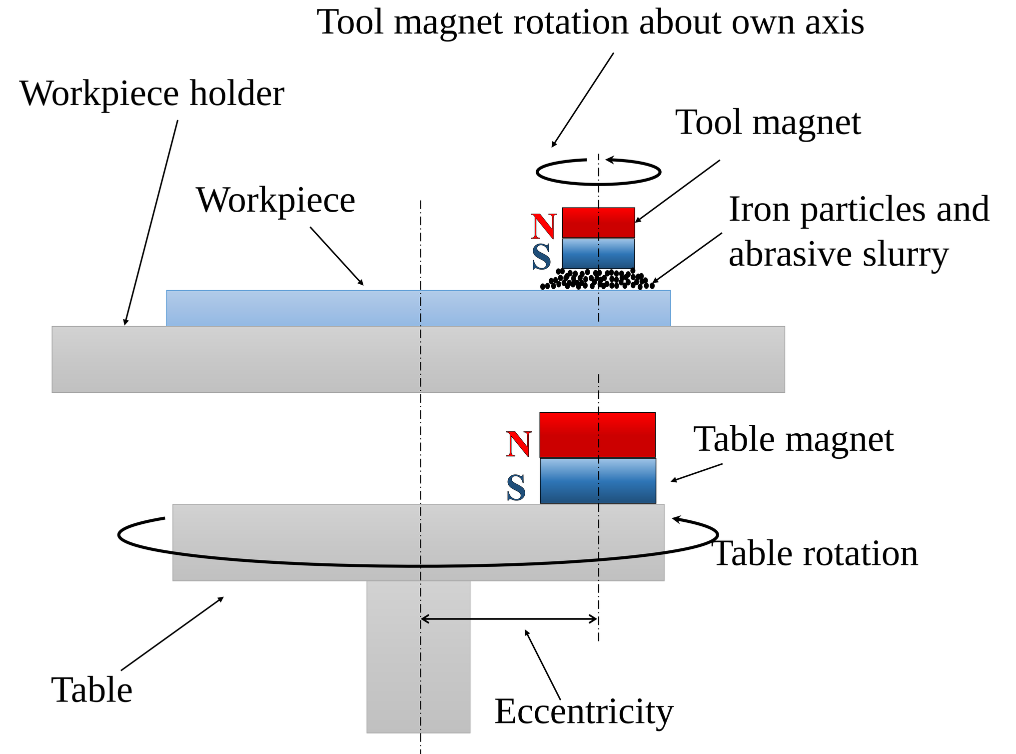


Solid state lasers have traditionally used single crystal gain media. However, polycrystalline ceramics have garnered an increased level of interest for high-power laser applications. To realize their full potential, polycrystalline ceramics have a variety of light-scattering sources that must be overcome. Internal scattering sources have been diminished substantially with modern fabrication techniques; however, surface roughness can still have great effects on lasing ability.

Transparent ceramic optical properties



Processing Principle



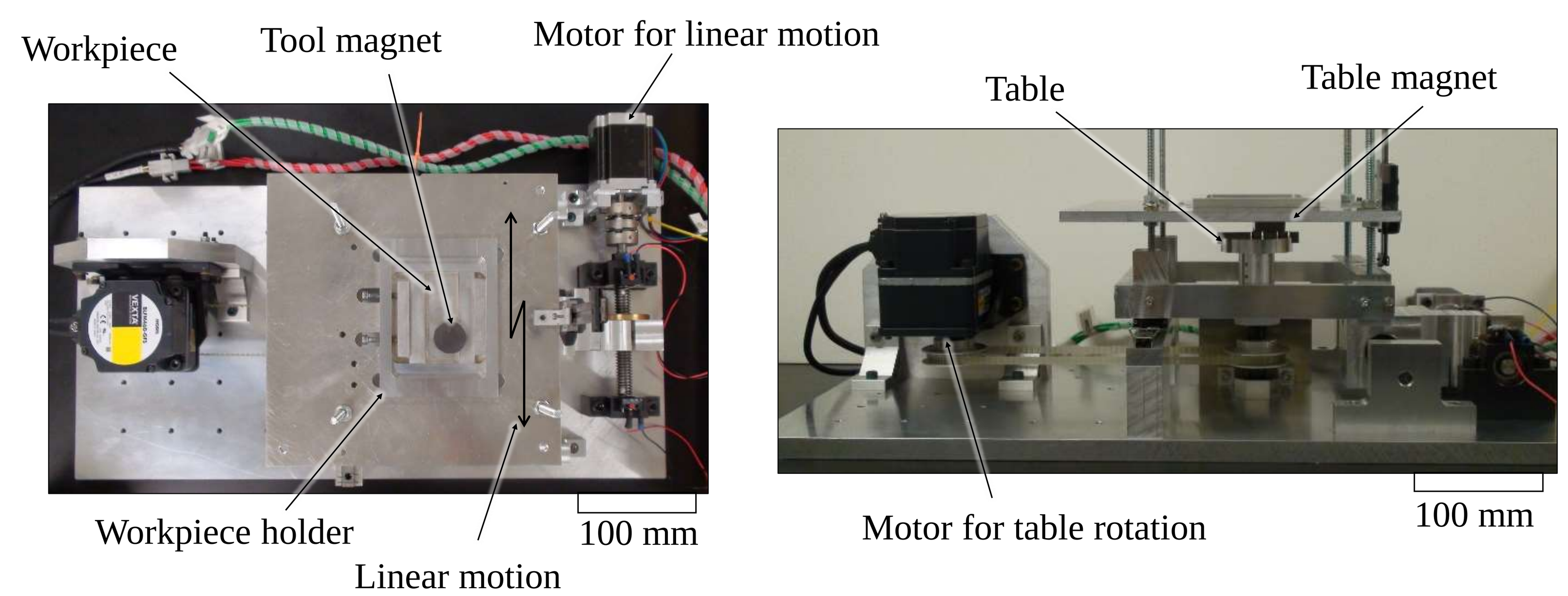
Magnetic force: $F = V\chi H grad(H)$

V: Volume of magnetic tool or ferrous particle

χ: Susceptibility

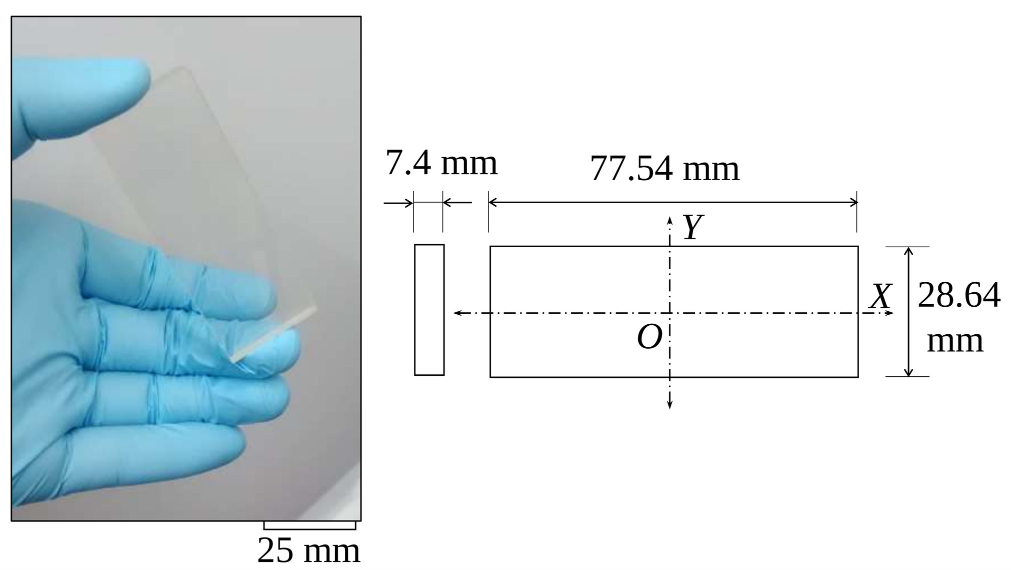
H: Magnetic field

Experimental Setup



A permanent magnet (*table magnet*) is attached to a rotating table. The workpiece is secured to a holder above the rotating table, and iron particles are placed on the workpiece. An additional permanent magnet (referred to as the *tool magnet*) is put on the iron particles. The iron particles align with the magnetic field lines generated between the table magnet and tool magnet creating a freeform brush. Abrasives are then introduced into the finishing zone between the iron brush and the workpiece surface. As the table magnet rotates about a central axis, the tool magnet and iron particles are pulled across the surface of the workpiece, providing the motion required for finishing.

Experimental Conditions

Workpiece	Pure YAG ceramic sample 
Linear motion travel distance	40 mm
Linear motion speed	1 mm/s
Table magnet revolution	400 min^{-1}
Clearance between table magnet workpiece surface	10.56 mm
Magnetic flux density at finishing area	120 mT
Iron particles	1, 7, 44, 44-149, μm diameter
Abrasive	0-0.1, 0-0.25, 0-0.5, 0-2 μm diameter diamond 3 wt% 7 nm silica particles in deionized water

Acknowledgements

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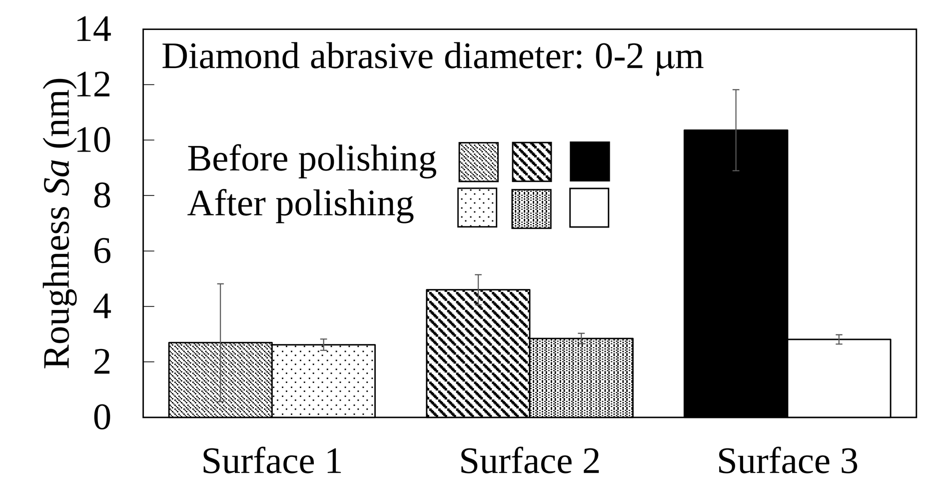
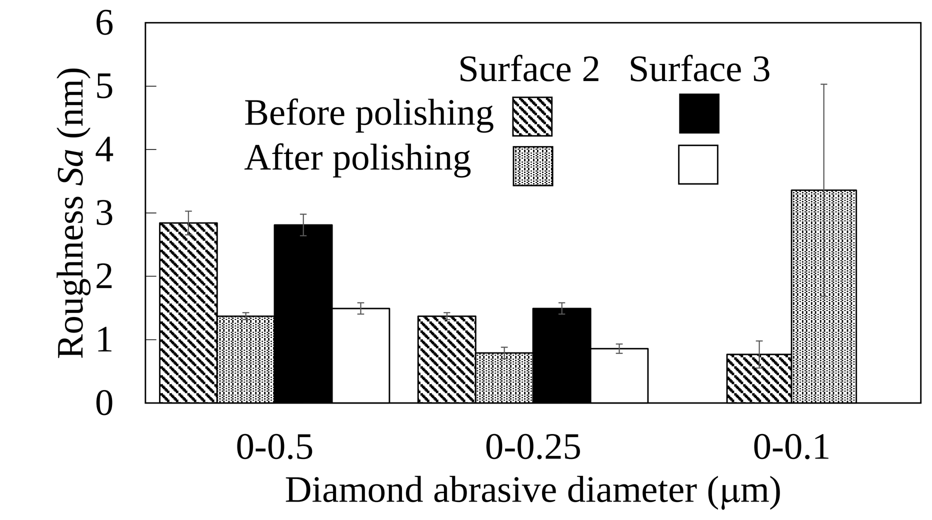
Results

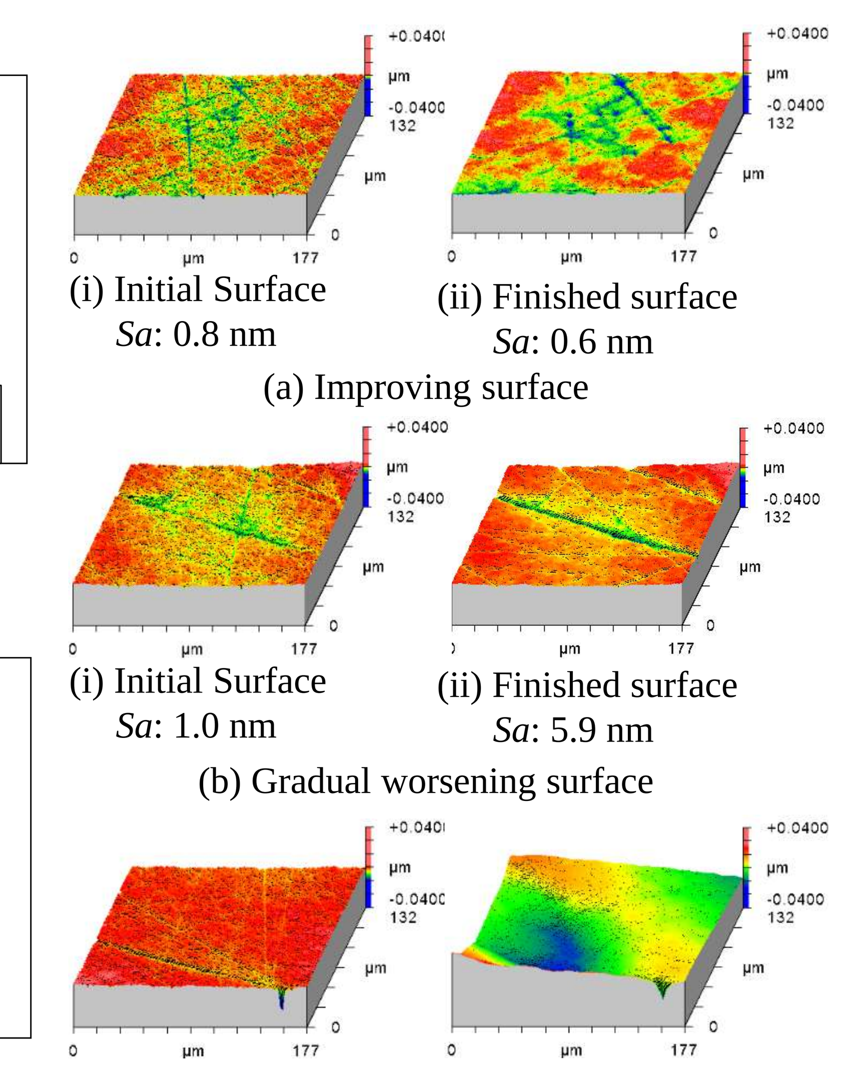
As the diamond abrasive size was stepped down, the roughness decreased and the standard deviation stayed relatively small, showing the uniformity of the surface. After polishing for 60 min with the 0-0.25 μm diameter diamond abrasive the surface roughness reached sub-nanometer levels. However, it was found that once the diamond abrasive size dropped to 0-0.1 μm, the roughness increased substantially for Surface 2 and did not continue to decrease. The standard deviation of the measured data points also increased substantially, suggesting that the effect was not uniform across the surface.



30 min polishing



60 min polishing



(i) Initial Surface *Sa*: 0.8 nm (ii) Finished surface *Sa*: 0.6 nm
(a) Improving surface

(i) Initial Surface *Sa*: 1.0 nm (ii) Finished surface *Sa*: 5.9 nm
(b) Gradual worsening surface

(i) Initial Surface *Sa*: 1.0 nm (ii) Finished surface *Sa*: 5.9 nm
(c) Dramatic worsening surface

The grain size of this polycrystalline ceramic was found to be between 15 and 30 μm. The grain structure of the ceramic influenced the material removal as the iron particle size dropped below the material's grain size. When the size of the iron particle is smaller than the grain size, the iron particle presses abrasives into individual grains. The small iron particles can penetrate into the resulting cavities and material removal is increased at these sites. This results in uneven material removal between grains, and increased removal at the grain boundaries, causing the grain structure of the YAG ceramic workpiece to become increasingly apparent with additional polishing time. This held true for polishing with diamond abrasive and colloidal silica.
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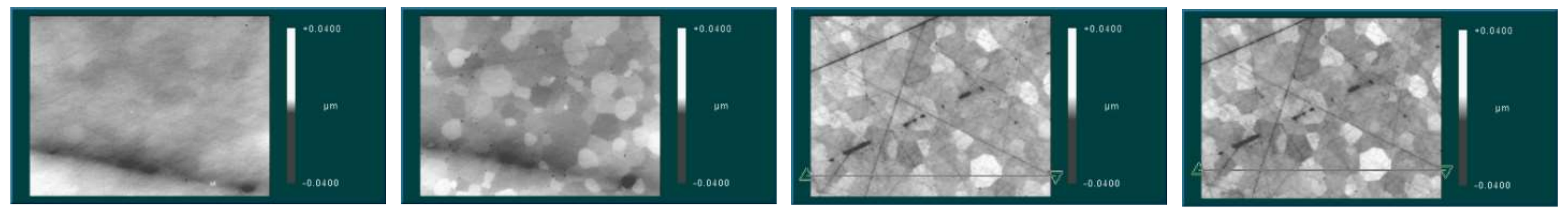

(i) 7 μm iron particles *Sa*: 0.8 nm (ii) 1 μm iron particles *Sa*: 1.1 nm
(a) 0-0.1 μm diameter diamond

(i) 7 μm iron particles *Sa*: 1.4 nm (ii) 1 μm iron particles *Sa*: 1.7 nm
(b) Colloidal silica

Conclusions

- MAF smooths transparent YAG ceramics to sub-nanometer levels despite large variability in initial surface conditions.
- Finishing sub-nanometer surfaces with extremely fine diamond abrasive causes average roughness to rise as a result of varying defect modification across surface.
- Finishing sub-nanometer surfaces with colloidal silica causes a widening of defects uneven material removal between grains
- Polishing with iron particles below the ceramic grain size caused uneven material removal between grains and increased removal at grain boundaries

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