Polishing Characteristics of Transparent Polycrystalline Yttrium Aluminum Garnet Ceramics Using Magnetic Field-Assisted Finishing

Transparent polycrystalline 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 to be doped in relatively 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 paper is to study the polishing characteristics of YAG ceramics using magnetic field-assisted finishing (MAF). MAF is a useful process for studying the polishing characteristics of a material due to the extensive variability of, and fine control over, the polishing parameters. An experimental setup was developed for YAG ceramic workpieces, and using this equipment with diamond abrasives, the surfaces were polished to subnanometer scales. When polishing these subnanometer surfaces with 0–0.1 μm mean diamond abrasive, the severity of the initial surface defects governed whether improvements to the surface would occur at these locations. Polishing subnanometer surfaces with colloidal silica abrasive caused a worsening of defects, resulting in increased roughness. Colloidal silica causes uneven material removal between grains and an increase in material removal at grain boundaries causing the grain structure of the YAG ceramic workpiece to become pronounced. This effect also occurred with either abrasive when polishing with iron particles, used in MAF to press abrasives against a workpiece surface, that are smaller than the grain size of the YAG ceramic. [DOI: 10.1115/1.4034641]

Introduction

Solid-state lasers have traditionally used monocrystalline gain media. The first such example was a ruby-based laser created by Maiman in 1960 [1,2]. Continuous-wave laser oscillation using single crystal Nd:YAG was successfully accomplished not long after, in 1964 [3]. Translucent YAG ceramics were developed as gain media in the 1980s; however, they performed poorly due to low-optical-grade properties [4–6]. It was not until the mid-1990s when Ikese et al. developed transparent Nd:YAG ceramics of high enough optical quality to produce successful laser oscillation [7]. Since this time, it has been shown that laser oscillations can be obtained with YAG ceramics, which are comparable or even superior to those of monocrystalline YAG [8,9]. Polycrystalline gain media can be scaled to much larger sizes, are relatively economical, and can undergo heavy doping [10–13]. As such, polycrystalline host materials have garnered an increased level of interest for high-power applications.

These advanced ceramics, however, have structural challenges that must be overcome. Conventional polycrystalline ceramics have a variety of light-scattering sources, which can result in lower laser power output and slope efficiencies. Refractive index modulation can occur at the grain boundaries, and any inclusions or pores can cause index changes. Birefringence can be a concern, as well as scattering at the surface caused by roughness [14,15].

The internal scattering sources have been diminished substantially with modern fabrication techniques; however, surface roughness can still have great effects on lasing ability. In addition to the scattering that can occur due to surface roughness, it has been shown that laser damage threshold is greatly affected by surface conditions [16]. Surface characteristics are important when bonding the ceramics to make a larger composite or when applying coatings. Defects in the bonding zone or under a coating can cause scattering centers in the interior of these composites. Since the surface finish of polycrystalline YAG ceramics significantly influences lasing performance, it is necessary to understand the polishing characteristics of this material.

Poly- and monocrystalline materials have been polished by a variety of techniques. Diamond is often used due to its relative hardness compared to that of the ceramics. Colloidal silica is also used for the polishing of ceramics due to its ability to chemically react with ceramic materials and reduce subsurface damage [17]. To better control the polishing of polycrystalline YAG ceramic, it is important to clarify the material removal mechanisms that these abrasives have on this material.

Magnetic field-assisted finishing (MAF) has proven to be a promising technology for overcoming problems associated with more traditional polishing techniques and the extensive variability of, and fine control over, polishing parameters makes it a useful process for studying the polishing characteristics of a material. Through control of magnetic fields, magnetic particles and abrasives can be manipulated against and across surfaces with precision. This process can be used with a large variety of abrasives, and cutting force and depth can be controlled through abrasive-
The polishing of polycrystalline YAG ceramic slabs. Due to the hardness and relative thickness (7.4 mm) of the YAG ceramic, a larger polishing force is required than when compared to the force necessary for 60 μm thick quartz polishing performed by Yamaguchi et al. [19]. Nd-Fe-B rare earth tool and table magnets were thus selected. The workpiece is held in place by a nonferrous holder, and the permanent table magnet is placed on a ferrous bar fixed to the rotating table. The distance between the bottom of the holder and table magnet is adjustable, and the holder table can move linearly, allowing for the polishing of the entire rectangular area of the surface.

As Fig. 3 shows, the iron particles initially line up along the lines of magnetic force between the tool magnet and workpiece surface. However, during rotation, the iron particles gradually climb to the uppermost surface of the tool magnet. As the table magnet rotates, the tool magnet and iron particles are dragged across the workpiece surface. The frictional force between the workpiece surface and loose iron particles naturally wants to drive the iron particles out of the interface between the tool magnet and workpiece surface. The iron particles in the interface push the iron particles near them, and the iron particles flow as a whole along the magnetic field lines to the top surface of the tool magnet. If nothing impedes this flow of the iron particles, a majority will eventually leave the interface and the tool magnet will directly interact with the workpiece surface, damaging the workpiece. To prevent this from occurring, the tool magnet was fitted with a cap, which has a diameter larger than the tool magnet. The cap was selected to be a weak rubber magnet so that it will easily and securely attach to the uppermost surface of the tool magnet. The rubber magnet cap (magnetic flux density: 1.2 mT at the center of the surface) does not greatly influence the magnetic field of the Nd-Fe-B tool magnet (magnetic flux density: 285.7 mT at the center of the surface).
of the surface) due to its relative weakness. This cap physically prevents the iron particles from being pushed to the top surface of the tool magnet by the iron particles in the interface. The iron particles cannot flow from the interface and the iron brush is maintained, preventing any contact between tool magnet and workpiece.

Polishing Characteristics

In this study, polishing experiments of polycrystalline YAG ceramic slabs focused on abrasive type, iron-particle size, and polishing time. The first set of experiments was performed to analyze the effects of diamond abrasive size on surface roughness. These experiments allowed the surface to be brought to subnanometer arithmetic average roughness $S_a$. The subsequent experiments were performed to analyze the effects of fine diamond and colloidal silica on this subnanometer surface.

Creating smooth and consistent tool motion is necessary for achieving a fine polishing process. Through experimentation it was found that the table magnet revolution speed and the magnetic field intensity were contributing factors to successful tool motion. At slow table magnet revolution speeds, the tool magnet has a tendency to stutter in its motion, and at high speeds, the tool magnet can be thrown from the finishing area due to the centrifugal force. These trends were also confirmed in previous research [19]. The selected experimental conditions, listed in Table 1, produced the most stable tool motion and remained unchanged during the course of experimentation.

The center of the workpiece was found and designated as the origin of the Cartesian coordinates (Table 1). Surface roughness measurements were taken from the origin and every 1 mm for 10 mm in both the positive and negative $X$ directions. These are the locations of the 21 measurements referred to in the “Rough Polishing with Diamond Abrasive”, “Fine Polishing with Diamond Abrasive”, and “Fine Polishing with Colloidal Silica” sections.

Rough Polishing With Diamond Abrasive

The experiments presented in this section utilized 0.7 g of 44–149 μm mean diameter iron particles. Three different surfaces with dissimilar initial surface conditions (referred to as surface 1, surface 2, and surface 3) were polished with 0–2 μm diameter diamond abrasive for 30 mins. Surfaces 2 and 3 were then polished with 0–0.5 μm and 0–0.25 μm diameter diamond abrasive for 60 mins in series. Surface 2 was subsequently polished with 0–0.1 μm diameter diamond abrasive for 60 mins.

Figure 4 shows the roughness $S_a$ averaged across all 21 measurement points, before and after every polishing stage for each surface. Figure 5 displays a three-dimensional oblique plot of a representative point from each surface before and after polishing with 0–2 μm diameter diamond abrasive. Surface 1 was heavily pitted and has a substantial standard deviation across the various measurements of the surface (Fig. 4). Surface 2 had many pillarlike structures and an average roughness that is nearly double that of surface 1. Surface 3 had many deep scratches and an average roughness that is more than double that of surface 2. After the process was performed, all three surfaces had similar roughness values with a similarly low standard deviation across the measurement points.

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 mins
with the 0–0.25 μm diameter diamond abrasive, the surface roughness reached subnanometer levels for both surfaces 2 and 3. 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. To better understand the mechanisms behind this behavior, subsequent experiments were performed on the effects of polishing this material with fine diamond abrasive once the surface had already achieved subnanometer levels.

**Fine Polishing With Diamond Abrasive**

A series of polishing tests were performed to better understand the behavior of this material in response to polishing with 0–0.1 μm diameter diamond abrasive. Prior to every experiment performed in this section, the surface of the workpiece was returned to the subnanometer scale, using the 0–0.25 μm diameter diamond abrasive polishing process described in the “Rough Polishing with Diamond Abrasive” section.

The workpiece, after being returned to the subnanometer scale, was polished in 5 mins increments for 15 mins using the 0–0.1 μm mean diameter diamond abrasive with 0.7 g of 44–149 μm iron particles. This process was performed twice, referred to as fine diamond test 1 and fine diamond test 2. The roughness Sa at all 21 measured positions after each 5 mins polishing stage for fine diamond test 1 and fine diamond test 2 are shown in Figs. 6 and 7, respectively. There did not appear to be a direct correlation between the measurement location and the category the surface at that position fell within.

Fine diamond test 1 resulted in positions with roughness values that had dramatic worsening, average gradual worsening, and average gradual improvement with increased polishing time. Fine diamond test 2 resulted in three positions with average gradual worsening, whereas the remaining positions had average gradual improvement with increased polishing time.

Figure 8 shows three-dimensional oblique plots of representative examples of positions that saw gradual improvement, gradual worsening, and dramatic worsening. The gradually improving
position, indicated in Fig. 6 and displayed in Fig. 8, was found at \(X = -2\) mm in fine diamond test 1. After the 0–0.25 \(\mu\)m diameter diamond abrasive preprocessing phase, the surface at the improving position had an initial roughness of 0.8 nm \(Sa\). The deepest valley was measured to be 12.5 nm, and the deeper scratches were relatively evenly distributed across the surface. The widest valleys present on the surface were roughly 3 \(\mu\)m. However, the widths of most defects were less than 2 \(\mu\)m. After polishing with the 0–0.1 \(\mu\)m diameter diamond abrasive for 5 mins, the roughness improved to 0.6 nm and continued to improve after 10 and 15 mins of polishing time.

The gradually worsening position, indicated in Fig. 7 and displayed in Fig. 8, was found at \(X = 6\) mm in fine diamond test 2. After the preprocessing stage, the surface at this worsening position had an initial roughness of 1.2 nm \(Sa\). The deepest valley was measured to be 15.3 nm, and the deeper scratches were relatively evenly distributed across the surface. The widest valleys present on the surface were roughly 3 \(\mu\)m. However, the widths of most defects were less than 2 \(\mu\)m. After polishing with the 0–0.1 \(\mu\)m diameter diamond abrasive for 5 mins, the roughness worsened to 1.3 nm, and while the depth of the valley did not significantly change, the width grew to approximately 6–8 \(\mu\)m. The surface continued to gradually worsen after 10 and 15 mins of polishing time.

The dramatic worsening position, indicated in Fig. 6 and displayed in Fig. 8, found at \(X = 6\) mm in fine diamond test 1, had a lower initial roughness (1.0 nm \(Sa\)) when compared to the gradually worsening position; however, the deepest valley at this position was measured to be 27.7 nm and two relatively deep scratches were located in close proximity. The scratches were not substantially wider than the scratch located on the gradually worsening position; however, after polishing with the 0–0.1 \(\mu\)m diameter diamond abrasive for 5 mins, a large section of material was removed from the area between these deep scratches. The roughness at this position worsened dramatically as a result. The roughness improved gradually with each additional 5 min process. After the chipping occurred, the sharp edges of the chip zone were smoothed. This caused a leveling of the surface and a drop in the roughness value. The deepest valley at every position was recorded prior to polishing with fine diamond, and in general, the width of the defect was related to the depth: deeper defects were generally wider than shallow defects. It was found that the positions that saw an average gradual worsening had an average initial deepest valley of 18.8 nm in fine diamond test 1 and 14.2 nm in fine diamond test 2. The widths of these defects were generally in the 3–6 \(\mu\)m range. After polishing for 5 mins, the widths of the larger defects increased to approximately 5–10 \(\mu\)m. The widths continued to increase to 10–15 \(\mu\)m and 15–20 \(\mu\)m after 10 and 15 mins of polishing time, respectively.

Positions that saw an average gradual improvement had an average initial deepest valley of 12.9 nm in fine diamond test 1 and 8.8 nm in fine diamond test 2. While some localized defects on these surfaces were approximately 5 \(\mu\)m wide, the majority of the defects were less than approximately 2 \(\mu\)m. The larger defects widened with increased polishing time; however, the majority of the defects reduced in width.
The depth and width of the surface scratches prior to polishing with a slurry of 0–0.1 μm diameter diamond abrasive, and 44–149 μm iron particles have an effect on whether the roughness of the surface will improve or worsen with fine diamond polishing. The iron particles must press the diamond abrasive into and across the surface for material removal to occur. When the width of a defect is sufficiently small, the iron will pass over the defect as it moves across the surface. Despite the possibility of abrasive entering the defect, there is no material removal within the defect as the iron cannot apply pressure to the abrasive in that region. Material is removed from the surface surrounding the defect, effectively reducing the depth and width of the scratching.

The larger the initial width of the defect, the more likely an iron particle is able to partially penetrate the defect. The iron particle is then able to press the diamond abrasive into the workpiece in the defect and cause material removal. This causes a widening of the defect, which, in turn, allows more iron to penetrate and more material to be removed within the defect. When several large defects are in close proximity, chips can form and be ejected from the surface.

The average roughness Sa across all 21 measurement positions of the surface prior to fine diamond test 1 was 0.8 nm and the average deepest valley was 15.5 nm. The initial surface had many deep and wide scratches, which worsened with additional polishing time. The surface had positions with high concentrations of scratching resulting in chipping in these regions. At this level of roughness, the chipping that occurred during polishing had a much more dramatic effect on the roughness values of the surface than the subsequent smoothing that this size abrasive could produce. Due to the defects existing on the initial surface, the surface roughness averaged across all measured points continued to climb with additional polishing time for fine diamond test 1. The standard deviation of the measured roughness values increased with polishing time showing the unevenness of the process across the surface.

The average roughness of the surface prior to fine diamond test 2 was higher at 0.9 nm; however, the average deepest valley was only 9.5 nm. The scratching on the surface prior to fine diamond test 2 was much more evenly distributed and not of the same depth and width as in fine diamond test 1. Despite having a few measurement positions see a gradual worsening, the average roughness across all measurement points improved. However, the standard deviation of the measured roughness values continued to climb as the disparity between the improving positions and worsening positions increased.

When polishing a surface with subnanometer roughness values with 0–0.1 μm mean diameter diamond abrasive, it became apparent that the specific features left on the surface as a result of the preprocessing stage drive the polishing characteristics of this process. In contrast to the experiments performed in section “Rough Polishing with Diamond Abrasive”, the initial surface conditions and localized defects had a significant effect on the resulting surface after polishing. The surface prior to polishing with fine diamond needs to have minimal, disperse scratching to see an improvement in average surface roughness with continued polishing time.

To further understand the effect of the iron particle size in the polishing process, the workpiece, after being returned to the subnanometer scale, was polished using the 0–0.1 μm diameter diamond abrasive with three decreasing sizes of iron particles (44, 7, and 1 μm mean diameter) in series for 5 mins each. This process was performed twice, referred to as fine diamond test 3 and fine diamond test 4.

The roughness Sa, averaged across all 21 measured positions, after each 5 mins polishing stage for both fine diamond test 3 and fine diamond test 4 are shown in Fig. 9. The average roughness increased after polishing with 44 μm mean diameter iron particles from 0.9 nm to 1.7 nm for fine diamond test 3 and from 0.9 nm to 1.6 nm for fine diamond test 4. The average roughness then decreased after polishing with 7 μm mean diameter iron followed by an increase with the 1 μm mean diameter iron.

Figure 10 shows the topography of a representative measurement position (X = −2 mm, test 2) after each 5 mins of polishing. Similar to polishing with the 44–149 μm iron particles, the relatively shallow defects were removed, and the severity of the deep defects were intensified when the surface was polished with the 44 μm mean diameter iron particles.

The depth of the deepest valley, averaged across all 21 measurement positions prior to polishing, was 11.5 nm for diamond test 3 and 11.8 nm for diamond test 4. The widths of the defects were minimal. Through the last set of experiments described in this section, it was found that surfaces with these levels of scratching were prone to improving with extended polishing time using the fine diamond abrasive and 44–149 μm mean diameter iron particles. However, the surface roughness increased with the use of a mixture of fine diamond abrasive and 44 μm mean diameter iron particles.

Defects that would have otherwise been reduced by the large 149 μm iron particles passing over the scratches were instead worsened by the 44 μm iron particles that could penetrate into the defect. The total mass of the iron particles was held constant between experiments; therefore, more 44 μm iron particles are available to penetrate the defects when compared to the previous test with 44–149 μm iron particles. Larger scratches worsened at a more substantial rate resulting in an overall decline in the quality of the surface.

When the iron size was reduced to 7 μm mean diameter, the roughness value of the surface improved. Despite the reduced size of the iron particles, which allowed them to penetrate smaller defects, the magnetic force acting on the iron particles pressing the abrasive into the workpiece surface was greatly diminished.
As described by Eq. (1), the magnetic force acting on the iron particle pressing the abrasive against the surface is proportional to the volume of the iron particle.

When the force from the iron particle is reduced, the depth of cut and cutting force of the diamond abrasive are diminished. Despite the small iron particle being able to penetrate the defects, the diamond abrasive does not attack the material as aggressively and the defects are smoothed instead of worsened. However, despite being very subtle, the grains of the polycrystalline ceramic started to become pronounced, and this effect was further intensified as a result of polishing with the 1 μm mean diameter iron particles.

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. Again, the force pressing the diamond abrasive against the surface of the workpiece drives the material removal. When the size of the iron particle is larger than the grain size, the iron presses abrasives into and across multiple grains simultaneously. The magnetic force acting on the large iron particle, pressing the abrasive into the surface, is relatively large. The cutting force and depth of cut is not drastically influenced by minor variations in strength between grains and grain boundaries. This results in relatively consistent material removal between grains.

When the size of the iron particle is smaller than the grain size, the iron particle presses abrasives into individual grains. The magnetic force acting on the small iron is relatively small and minor variations in strength between grains and grain boundaries can influence cutting depth of the abrasive. Moreover, the small iron particles can supply force directed at individual grain boundaries. 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.

Fine Polishing With Colloidal Silica

To better understand the polishing effects of colloidal silica on transparent YAG ceramics, a series of polishing tests were performed using a slurry of 3 wt. % silica particles (7 nm mean diameter) in de-ionized water. Prior to every experiment performed in this section, the surface of the workpiece was returned to the sub-nanometer scale, using the 0–0.25 μm diameter diamond abrasive polishing process described in the “Rough Polishing with Diamond Abrasive” section.

The initial set of tests, similar to the experiments presented in the “Fine Polishing with Diamond Abrasive” section, used 44–149 μm iron particles, and the surface was polished with the colloidal silica in three 5 mins increments for 15 mins total. This test was performed twice: referred to as silica test 1 and silica test 2.

The roughness Sa, averaged across all 21 measured positions, after each 5 mins polishing stage for both silica test 1 and silica test 2 is shown in Fig. 11. The average roughness increases with each additional polishing stage.

Figure 12 displays the topography of a representative measurement position (X = −5 mm, silica test 2). As shown, while the minor defects dissipate, some of the larger defects intensify. More notably, despite the iron particle size being larger than the grain size, the grains of the polycrystalline ceramic became increasingly apparent and roughness continued to rise.

This shows that, despite having iron size above the grain size of the material, this process results in uneven material removal between grains and an increase in material removal at grain boundaries. While the iron particles must directly press diamond abrasive into the surface to remove material, this is not a requirement for colloidal silica due to its reactive nature with the YAG ceramic. The rate of material removal is effected by the amount of pressure applied and thus direct pressure from the iron particles pressing the silica into the surface will result in a high material removal at the interaction zone. However, material removal still occurs in regions such as defects and grain boundaries that these large iron particles cannot penetrate and apply direct pressure. Pressure is provided through the flow and downward force of the colloidal silica generated by the motion of the tool. Since the material removal rate is higher where the iron particles can supply direct pressure, the effect of the polycrystalline structure on the material removal is minimal although apparent.

To better understand the effect of the iron particle size in polishing with colloidal silica, the workpiece was polished using colloidal silica with three decreasing sizes of iron particles (44, 7, and 1 μm mean diameter) in series for 5 min each. This test was performed twice: referred to as silica test 3 and silica test 4.

Figure 13 displays the roughness, averaged across all 21 measurement points, for the surface after every polishing stage for both silica test 3 and silica test 4. Again, the average roughness increases with each additional polishing stage; however, there is a significant increase after polishing with the 7 μm mean diameter iron particles.

Figure 14 displays the topography at the center position (X = 0 mm) of the surface after each polishing stage during silica test 3. As shown by Figs. 14(a) and 14(b), after the 5 min silica process with 44 μm mean diameter iron particles, larger defects began to widen while minor scratches began to dissipate. There was a general increase in the roughness value of the surface.

After a process was performed with 7 μm mean diameter iron particles, the grains of the polycrystalline ceramic became very apparent. This effect was further intensified as a result of
flow along individual grains. Accordingly, these conditions resulted in the most dramatic reveal of the grain structure compared to other experiments presented in this paper. This is shown by the sharp and pronounced borders of the individual grains in the topography of the surface shown in Fig. 14(d).

Conclusion
The results of this study can be summarized as follows:

1. A Nd-Fe-B tool magnet with a cap is required for the polishing of transparent YAG ceramics with MAF. The Nd-Fe-B tool magnet was necessary for producing the magnetic force required for material removal. The cap, with a diameter larger than that of the tool magnet, was necessary to prevent iron particle motion, maintaining the iron particle brush between the tool magnet and workpiece surface.

2. MAF smooths transparent YAG ceramics with diamond abrasive to subnanometer levels despite large variability in initial surface conditions. When polishing with 0–0.1 μm mean diameter diamond abrasive, the initial surface conditions and specific defects influence the polishing process. The relationship between the size of the defects, the size of the iron particles, and the magnetic force acting on the iron particles pressing the abrasive against the surface drives the polishing characteristics of this process. When defects are sufficiently small, the iron particles will pass over the defect as they move across the surface. Material is removed from the surface surrounding the defect, effectively reducing the depth and width. However, when the defect is large, the iron particles can apply pressure onto the diamond abrasive within the defect, causing the defect to worsen. When several large defects are in close proximity, chips can form and be ejected from the surface. As the size of the iron particles is reduced, the magnetic force acting on the iron particles pressing the abrasive against the surface is lessened, resulting in diminished depth of cut and cutting force of the diamond abrasive which can improve surface roughness. However, when polishing is performed with fine diamond and iron particles smaller than the grain size of the YAG ceramic, uneven material removal between grains and increased removal at grain boundaries occurs. This caused the grain structure of the YAG ceramic workpiece to become increasingly pronounced with additional polishing time.

3. At subnanometer levels, MAF with colloidal silica abrasive caused a worsening of defects with increased polishing time, resulting in worsening roughness. Polishing with colloidal silica causes uneven material removal between grains and an increase in material removal at grain boundaries causing the grain structure of the YAG ceramic workpiece to become increasingly pronounced with additional polishing time. When polishing is performed with a mixture of colloidal silica and iron particles smaller than the grain size of the YAG ceramic, the uneven material removal between grains and increased removal at grain boundaries are more significant, causing the grain structure of the YAG ceramic to become very well defined.

Acknowledgment
This material is based upon work supported by the Air Force Office of Scientific Research (AFOSR) under Award No. FA 9550-14-1-0270. The authors would also like to express their thanks to Dr. Akio Ikesue for showing his support by providing workpieces for experimentation.

Nomenclature

\[
\text{grad}H = \text{magnetic field gradient}
\]

\[
H = \text{magnetic field intensity}
\]
min = minute
mT = millitesla
Sa = arithmetical mean height of the surface
V = volume of the magnetic particle
\( \chi \) = magnetic field susceptibility

References