Suitability of Igneous Rock for Precision Tooling

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ABSTRACT

Surface plates and blocking tools are commonly made of granite because of its good stability. But how stable is the granite, and which type of material is optimal? We have explored several materials and manufacturing processes for a 4-m aspheric reference surface that would serve as a tool for laying up composite optics. In this paper, we discuss the materials selection, stability to thermal and moisture effects, and parameters for processing the surface to give sub-micron accuracy and stability.

Keywords: Granite, igneous rock, processing

1. INTRODUCTION

Research was carried out at the University of Arizona Optical Sciences Center (UAOSC) under a contract with Composite Optics, Inc. (COI). The goal of this research was to investigate properties of different igneous rocks, such as granite, diorite and gabbro, in order to select the best possible material for a four meter diameter, convex, highly aspheric mandrel. The mandrel accuracy requirement was less than 0.5 microns rms figure error. The selection criteria for the candidate materials were based on pertinent material properties, as well as cost and schedule practicality, processing feasibility and various risk factors.

The scope of work for this study carried out at UAOSC involved investigating candidate materials, procuring and processing candidate samples, and testing the samples for dimensional stability after thermal/moisture cycling. COI carried out several experiments on relevant material properties of the candidate materials as well. These experiments included moisture absorption and moisture expansion measurements on material samples.

2. MATERIAL SELECTION

2.1 Definitions and terminology of rock types

There are three rock types; igneous, sedimentary and metamorphic. Igneous rock is formed from melted material, while sedimentary rock is formed from compacted wind or water deposited sediments, and metamorphic rock is formed from other existing rocks that are subjected to intense pressure or heat (below the melting point of the rock).[1] Of the three types, the igneous rock composition is the most isotropic, yielding more uniform material properties than the sedimentary or metamorphic rock. This fact makes igneous rock the logical choice of rock for an application that requires precision processing and stability.

Igneous rock is formed when molten or partially molten magma cools and solidifies. There are two broad categories of igneous rock, intrusive and extrusive. Intrusive igneous rock is formed below the earth's surface, therefore cooling and solidifying at a much slower rate than extrusive igneous rock, that is formed at the earth's surface. The difference in cooling time affects the amount of crystallization that occurs; therefore slowly cooling rock will form larger crystals and have a larger grain structure than quickly cooling rock.[1] Extrusive igneous rock is typically found in small column or boulder form, and large pieces are very rare. In comparison, intrusive igneous rock is easily found in large pieces. Therefore, of the two categories of igneous rock, the intrusive type was chosen as the best candidate to yield a four meter part.

The constituents of intrusive igneous rocks are mostly quartz, feldspar, mica and hornblende. These rocks can be further classified by their chemical compositions. The three classes that are commonly quarried are felsic, intermediate and mafic, which differ mostly by the amount of quartz found in them. The felsic class typically contains greater than 20% quartz, while the intermediate class contains less than 10% and the mafic class contains no quartz. The types of rock

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identified under these classes are granite (felsic), diorite (intermediate) and gabbro (mafic). The amount of quartz in each of these types of igneous rock was influenced by the length of time the molten magma had to cool down and solidify. Longer cool down times allowed for crystallization to occur, therefore increasing the amount of quartz formed in the rock.[1]

2.2 Rationale for choosing igneous rock

The decision to explore using rock material for a large, stable mandrel was made by COI in order to meet the schedule and cost goals of their program. Based on availability and suitability, the intrusive igneous rock class was determined to have the best potential to meet the needs of the program. Intrusive igneous rock has heritage for use as a suitable substrate in applications that require stability, such as continuous polisher and coordinate measuring machine bases, and also in applications that require precision surfaces, such as surface plates. This heritage, coupled with substantial savings in delivery schedule and cost, make intrusive igneous rock an attractive alternative to other materials traditionally used in this application, such as low expansion glassy ceramics.

Other materials that were considered based on their delivery and cost were synthetic granite, graphite, steel and aluminum. It was determined that synthetic granite was not a good choice because of processing issues relating to the difference in hardness of its epoxy content and the aggregate rock. Graphite was eliminated from consideration due to the fact that it could not be obtained in a monolithic form, which led to concerns on interface properties between pieces and stability of the assembled pieces. Steel and aluminum were eliminated by virtue of their material properties. The coefficient of thermal expansion (CTE) of steel is two to three times greater than intrusive igneous rock, while the CTE of aluminum is four to six times greater. Given that the decision to utilize intrusive igneous rock was now made, the next step was to determine which type to use; granite, diorite or gabbro.

2.3 Material selection criteria

The list of candidate materials was initially determined by surveying surface plate manufacturers on their material options. This proved to be very informative in that the material properties that are pertinent to surface plates may not be pertinent to our application. For example, in tool room and quality inspection applications, it is important for surface plates to be resistant to wear by metal objects sliding across their surfaces, thus affecting the surface accuracy. To minimize this effect, most surface plates offered for these applications contain a high quantity of quartz in order to yield a harder, wear resistant surface. These substrates are felsic class igneous rock, such as granite. However, in our application, wear is not an issue, therefore the quartz content was not considered to be beneficial in this context.

The survey of surface plate manufacturers also revealed that for high precision gauging and metrology applications, a mafic or intermediate class igneous rock, such as gabbro or diorite was used instead of granite. The reason given for this by the manufacturers was that granite is more porous than gabbro or diorite, and therefore is less stable due to its propensity to absorb moisture and subsequently expand or contract with changes in humidity. This property is very relevant to our application, not only due to the stability requirements of its end use, but also due to the manufacturing process, which utilizes water based slurries for grinding and polishing operations. If the substrate was continually expanding and contracting due to absorption and evaporation of moisture, then it would be virtually impossible to meet the figure goals of the program. Therefore, moisture absorption of the candidate materials was one of the key properties studied.

Other mechanical properties that were deemed relevant to the project goals were CTE, including hysteresis, natural defects, such as large regions of inhomogeneity and hidden cracks, and processing characteristics. In order to mitigate the risk of obtaining a substrate with a natural defect that would adversely affect the quality of the final part, it was decided to choose a quarry vendor that would rough machine the part to a near net shape in order to expose hidden defects near the usable surface. This would be done prior to acceptance for use in the program. Another, equally important issue was the availability of the substrate material in the size required to yield a monolithic part four meters in diameter and three quarters of a meter thick.

The following selection criteria were generated in order to assist in determining if a material was a viable candidate:

- Four meter size availability
- Lead time for part
- Cost of part
- Dimensionally stable vs. moisture
- Dimensionally stable vs. temperature
- Vendor responsibility for part through rough machining

2.4 Material candidates

After performing the preliminary research, it was decided to choose one of each of the types of intrusive igneous rock, a granite, a diorite and a gabbro. Of the granites, there were several candidates that met the size availability criterion, and they were almost identical in their mechanical properties. Therefore, the ability of the vendor to rough machine the substrate prior to acceptance was used as the deciding factor on which granite to study. Based on this, a granite, called Barre Gray, was selected. The diorite that was selected was Academy Black. The gabbro that was selected, was Rustenburg, however, it was eliminated from the candidate list due to a lack of history in obtaining large enough substrates and the fact that domestic vendors would not be responsible for the substrate through rough machining. None of the other gabbros were able to meet this criterion, so gabbro was eliminated as a potential candidate. A summary table of the candidates and their pertinent properties is shown below:

Rock Name	Classification	Water Absorption	CTE	Density
Barre Gray	Granite	0.22%	3.4E-6/F	167 pcf
Academy Black	Diorite	0.11%	3.8E-6/F	183 pcf
Rustenburg	Gabbro	0.09%	2.2E-6/F	230 pcf

2.5 Material study test tasks

A thorough study of the two remaining candidates was carried out with the specific goals of assessing the feasibility of processing each type and verifying the dimensional stability of each type as a function of moisture and thermal exposure. The tasks of this study were as follows:

- Procure 0.3 meter and 1 meter diameter samples of candidate materials and process samples into concave spheres.
- Perform a baseline interferometric measurement on the finished samples.
- Thermally cycle the finished samples.
- Re-measure the sample surfaces interferometrically to detect figure change.
- Procure sample coupons of candidate materials for moisture uptake tests at COI

2.6 Material processing

The material processing parameters for the one meter samples were determined by evaluating different processes on the 0.3 meter samples. The effect of increasing the lapping pressure from 0.25 psi to 2.0 psi was of particular interest due to the intended use of a ring tool on the four meter part, which would produce a localized pressure of 1 psi. Another point of interest was whether polyurethane pads could be used as the polishing medium, rather than pitch. Also, based on suggestions from surface plate manufacturers, a moisture barrier was created on the top surface of each sample by applying a thin layer of lightweight oil. The rationale behind the moisture barrier was to prevent expansion and contraction of the part due to water absorption and evaporation during processing with water based slurries.

During all processing steps, both one meter parts were mounted on 3-point support systems. The parts were generated with a fixed diamond abrasive wheel, and during generating operations, it was obvious that the Barre Gray sample was harder than the Academy Black sample, due to its higher quartz content. After both parts were generated, they were allowed to dry out for a one week period. After this period, a lightweight oil mixture was applied to the top surface to act as a moisture barrier from the water based slurries. Also, a plastic skirt was attached to the side of the parts to prevent moisture from absorbing through the side. Approximately full size tools were used for grinding the parts spherical. The experiments on the 0.3 meter parts showed that there would be no adverse effect caused by using higher lapping pressure.

Therefore, it was decided that one sample would be processed at 1 psi, and the other at 0.3 psi. Since the Academy Black material is softer than the Barre Gray, it was decided to take a worst case approach and use the higher pressure on the softer material. The tools were faced with quarry tile, which was slightly softer than the Barre Gray and slightly harder than the Academy Black. The parts were then ground with aluminum oxide, starting with 40 micron grit and ending with 5 micron. The Barre Gray sample was processed using run times that were equivalent to those used on fused quartz. The same run times were used while processing the Academy Black sample, however, based on visual inspection, the Academy Black sample needed roughly 75% of the run time that was required for Barre Gray. After the parts were ground, the tile tools were covered with polyurethane squares for polishing. The parts were then polished with cerium oxide. It took approximately 40 hours to achieve a polish on the parts.

2.7 Surface figure error

After the parts were polished out, they were tested interferometrically along a vertical path. The vertical tower was equipped with two interferometers, one each for an interior and exterior test path, in order to avoid conflicts in testing both parts. The interior path utilized a phaseshifting infrared interferometer, and the exterior path utilized a phaseshifting visible wavelength interferometer. Upon visual inspection, the Academy Black piece had a finer grain structure and higher reflectivity than the Barre Gray piece. Therefore, the Academy Black part was set up under the visible wavelength interferometer, while the Barre Gray part was set up under the infrared interferometer.

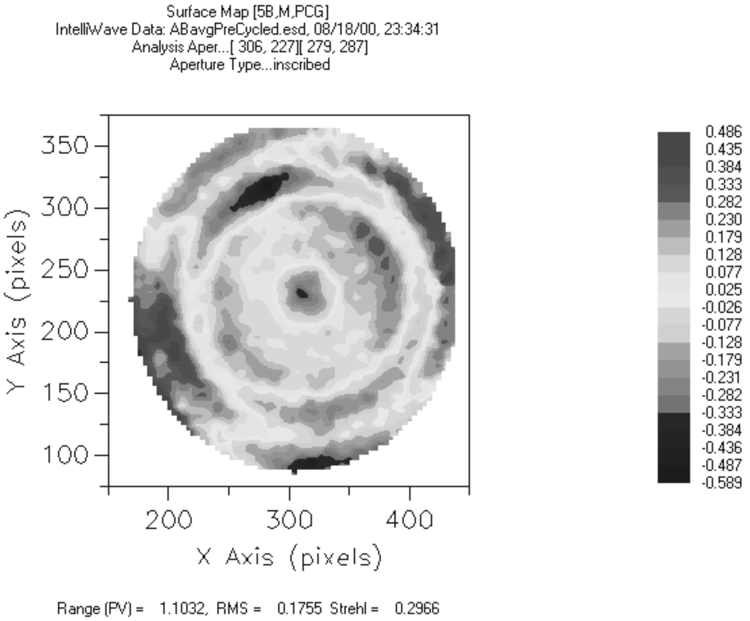

Figure 1: Surface map of Academy Black showing 0.1 micron rms surface error

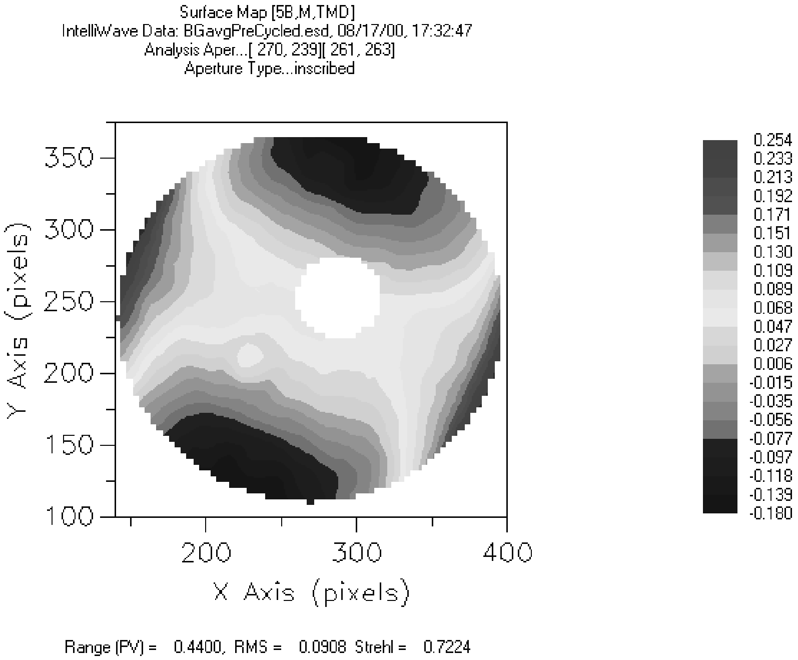

Figure 2: Surface map of Barre Gray showing 0.95 microns rms figure error

During the processing operations, there were no noticeable flaws in either sample. However, a major flaw was discovered in the Barre Gray when the sample was tested interferometrically. The phase map showed that the surface error was approximately 5 µm p-v, and was severely astigmatic as can be seen in Figure 2. Astigmatism of this magnitude is very unlikely to occur under normal spherical processing operations, therefore the surface was scrutinized for imperfections. A band of slight discoloration approximately 6” wide was evident on the sample, and was aligned directly along the axis of the astigmatism. The discoloration represents a variance in the material composition of the sample, and a corresponding variance in material strength. The implication of this flaw is significant, especially in light of the fact that the sample was taken directly off of the substrate designated for the 4 meter part. In comparison, the Academy Black sample exhibited only 0.7 µm p-v figure error, as can be seen in Figure 1.

2.8 Thermal exposure

The final portion of the material selection study at UAOSC involved verifying the dimensional stability of the one meter samples as a function of thermal exposure. The samples were measured prior to thermal cycling to establish a baseline data set. The samples were then thermally cycled from 20 °C to 50 °C three times, allowing for 0.1 °C ramp rates and 30 minute soak times at 50 °C. After thermal cycling, the samples were re-measured interferometrically to check for a change in surface figure, which would indicate that the material is not dimensionally stable. The results of this test show that the Barre Gray sample changed by 0.25 µm rms and that the Academy Black sample changed by 0.05 µm rms. Additionally, the appearance of the change in the Academy Black data indicates that it is dominated by a shearing error that is due to mapping effects, and not real surface changes. This implies that the real figure change is less than the computed change of 0.05 µm rms. Conversely, the appearance of the change in the Barre Gray data does not appear to be caused by a shearing error, implying that the computed error is real. The following figure shows the subtracted surface maps for both parts, showing the figure change after thermal cycling.

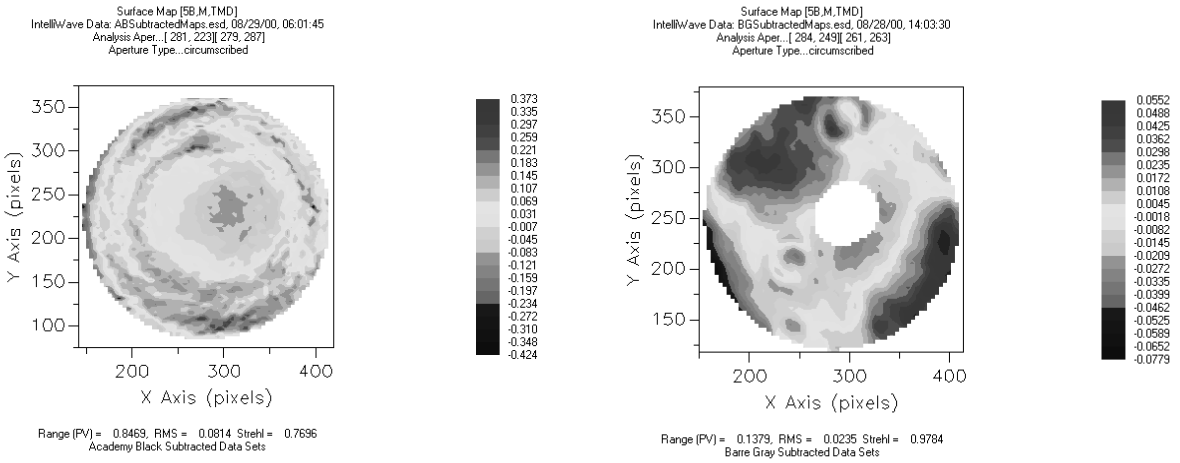

Figure 3: Subtracted surface maps after thermal cycling parts (note that the Barre Gray data was taken at 10.6 microns and the Academy Black was taken at 0.6328 microns)

2.9 Moisture Exposure

Experiments conducted by COI were performed in order to evaluate the effect of moisture exposure on dimensional stability. There were basically two experiments that were performed. The first experiment measured the maximum strain in the samples as a function of moisture exposure. The test configuration consisted of samples placed vertically in a container that were immersed in tap water up to 80% of their height. The longitudinal strains were measured for two complete moisture absorption and desorption cycles in order to check for hysteresis. After the total strain began to equilibrate for a period of 24 hours, the samples were dried at ambient temperature in a nitrogen environment. Following moisture cycling the thermal expansion of the sample was measured in the range of 75° F to 100° F. The coefficient of thermal expansion was calculated and used to remove the effects of thermal expansion due to temperature variation. This experiment was carried out prior to choosing Academy Black as a candidate, and instead compared Barre Gray to another granite called Sierra White. The quartz content in these two granites differed by roughly 8% (20% in Barre Gray and 28% in Sierra White). The data showed that the maximum strain in the Sierra White was 50% higher than that of the Barre Gray, which is equivalent to showing that the coefficient of moisture expansion is greater in Sierra White.

The second experiment measured the maximum percentage weight gain in the samples by exposing them to 100% humidity, drying the water off the surfaces of the samples, weighing the samples, and repeating until the weight ceased to increase. The parts were then put into a desiccated chamber at an elevated temperature, and dried out in order to obtain the dry weight. This experiment included a sample of Academy Black. The results of this experiment showed that the moisture uptake was highest for Sierra White, and lowest for Academy Black. A summary of the experimental data is shown in the following table:

Rock Name	**Grain Structure Observed**	**Quartz Content**	**Max Weight Gain (moisture absorption)**	**Max Strain (moisture expansion)**
Sierra White	2 - 7 mm	28%	0.35%	118 ppm
Barre Gray	2 - 3 mm	20%	0.24%	74 ppm
Academy Black	1 - 3 mm	2%	0.16%	untested

By studying the data from both experiments, an initial correlation between moisture absorption and moisture expansion can be established. The amount of moisture expansion appears to be proportional to the amount of moisture absorption for Sierra White and Barre Gray granite. Two distinct differences between these two granites are the quartz content and grain structure, with the Sierra White having more quartz and larger grain size. The lower moisture absorption seems to be correlated to the amount of quartz in the material and the grain structure size of the material. Therefore, using these properties as a guideline, it was surmised by extrapolation that since the Academy Black had lower moisture absorption than the other two materials, that it would also have lower moisture expansion because of its smaller grain size and lower quartz content. This agrees with the assessment of the surface plate manufacturers that were surveyed. The physical explanation for the correlation between quartz content and grain size to moisture absorption may be that the crystalline quartz, being harder than the surrounding minerals in the rock, creates a pocket boundary as the rock settles over time, therefore creating more pores for water to absorb into.

3. CONCLUSION

Based on the selection checklist created for this study, two candidates were picked as potential materials for the four meter mandrel, Academy Black, a diorite, and Barre Gray, a granite. The results of this study show that the pertinent material properties of Academy Black are superior to those of Barre Gary for our application. This study also illustrates the potential use of this material as an affordable solution for applications that require a large, stable surface with submicron accuracy.

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