The Use of Aluminum Alloy Castings as Diamond Machining Substrates for Optical Surfaces

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Abstract

This paper will discuss the use of aluminum alloy castings as diamond machining substrates for optical surfaces. Surface texture, infrared reflectivity, and temporal stability results from cast diamond machined samples will be presented. Physical data on these alloys will be given along with casting considerations.

Introduction

The diamond machining of metal mirrors is a well established optical fabrication technology. (1) Aluminum alloys are preferred materials for diamond machining because they are inexpensive, single-point diamond machine easily, and have good reflectivity even uncoated. To date most diamond machined aluminum mirrors have been made from plate, rolled, extruded or forged wrought forms. Since these wrought materials are produced in commodity sized production runs of several tons typically, these alloys are not engineered for the diamond machining finishing process. In addition, when mirror geometries are unusual or complex (eg. light-weight applications) it is desirable to have the substrate produced by a near net shape technique.

Sand casting is a process for producing substrates to near net shape thereby eliminating much of the conventional milling wrought forms can require. In addition, since casting melts are comparatively small, component chemistries can be optimized for the diamond machining process. Historically, castings have not been used for diamond machining substrates because of impurities and porosity. Impurities will cause either accelerated wear or catastrophic damage to single-point diamond tools and the presence of porosity will result in unsatisfactory surface finishes.

[illegible] controlling the casting process, aluminum castings can be used to produce optical surfaces by diamond machining. The results and recommendations presented in this paper are based on castings produced and successfully diamond machined in the last eight months.

The Casting Process

Casting Considerations

During this study casting parameters were varied to determine which process control variables impacted the diamond machined surface texture. Four aspects of the casting process proved to be critical:

1. the control of compounding materials,
2. the control of hydrogen gas absorbed in the melt,
3. the removal of non-metallic compounds,
4. the rate of casting solidification.

The control of raw compounding materials is important in obtaining diamond machinable substrates. The use of virgin metallurgically pure ingots to start the process permits the end castings to have impurity levels below 0.1 percent. To maintain proper alloying chemistry no remelted gates, runners risers or returns from previous castings can be used.

To prevent porosity, hydrogren gas must be removed from the melt. Excessive levels of hydrogen can adversely influence the dimensional stability, metallurgical integrity and grain structure of the casting. In castings with porosity it is difficult to obtain optical quality surface finishes. To prevent hydrogen porosity sophisticated de-gassing methods and controls are required for both the melting and pouring process. Hydrogen levels measured from properly de-gassed cast samples have been measured between 0.05 and 0.30 ppm. These values being near the theoretical low limit.

The removal of non-metallic compounds from the melt and during pouring is essential for single-point diamond tool life. Minimal levels of non-metalics are maintained by using properly coated handling equipment for the molten metal. The proper design of the gating system for the casting can also assist in excluding impurities during the pouring process. These impurities can be held to less than 0.1 percent in the final cast product.

The rate of casting solidification has a pronounced affect on the diamond machined surface texture produced. Substrates produced by different cooling rates demonstrates the need for rapid directional solidification. To insure that the best aluminum grain homogeneity is at the optical surface, it is best to have the cooling of the casting occur isotropically from that surface.

Alloy Selection

Initially five different aluminum alloy casting materials were evaluated. None of the materials tried displayed excessive single-point diamond tool wear. The 535 and 850 alloys produced surface finishes that would be appropriate for ultra-precise mechanical components and plated optical parts. The 201, 713, and 771 alloys yielded, by diamond machining, surface textures suitable for many optical applications. As will be shown later these materials demonstrated surface finishes that compare with the wrought alloy 6061. Tables 1 and 2 show the chemical compositions and the mechanical property limits (minimum) for these alloys, with the wrought 6061 alloy shown for comparison. (2,3)

6061 wrought	201 cast	713 cast	771 cast
Mg 0.80-1.20	Cu 4.00-5.20	Zn 7.00-8.00	Zn 6.50-7.50
Si 0.40-0.80	Ag 0.40-1.00	Cu 0.40-1.00	Mg 0.80-1.00
Cu 0.15-0.40	Mg 0.15-0.55	Mg 0.20-0.50	Ti 0.10-0.20
Cr 0.04-0.35	Mn 0.20-0.50		Cr 0.06-0.20
Fe 0.70 max	Fe 0.15 max	Fe 1.10 max	Fe 0.15 max
Zn 0.25 max	Ti 0.15 max	Mn 0.60 max	Si 0.15 max
Mn 0.15 max	Si 0.10 max	Cr 0.35 mx	Cu 0.10 max
Ti 0.15 max		Si 0.25 max	Mn 0.10 max
		Ti 0.25 max	
		Ni 0.15 max	
others each 0.05 max	0.05 max	0.10 max	0.05 max
others total 0.15 max	0.10 max	0.25 max	0.15 max
remainder aluminum			

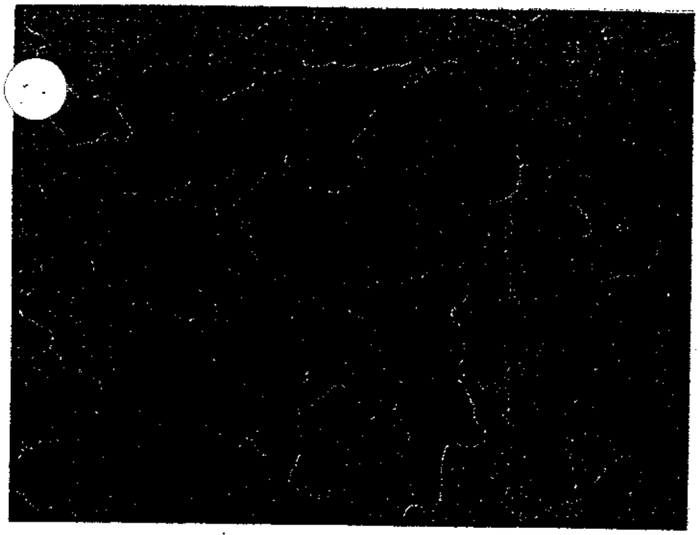
Table 1 - Aluminum Alloys Chemical Composition

Alloy	6061	201	535	713	771
Temper	T651	T7	T5	T5	T52
Tensile Strength					
Ultimate (ksi)	45	60	35	32	36
Yield (ksi)	40	50	18	22	30
% elongation in 2 inches	8.0	3.0	9.0	3.0	1.5

Table 2 - Aluminum Alloys Mechanical Property Limits (minimums)

Metallographic Analysis

Figure 1 shows a photograph of the microstructure from a cast 201 alloy. The sample was prepared by a Keller's etch process to enhance grain structure. This photograph shows the aluminum-rich dendrites surrounded by a solute-rich solid solution to form grains separated by a eutectic phase network. This is typical of the 201 alloys described in the literature. (4) What the photograph also shows is no porosity or impurities in the sample, which was typical of the substrates produced in this study.



Scale:

0.010 inch

Figure 1 - 201 Cast Aluminum Alloy Microstructure [after etch]

Diamond Machining Results

Sample Preparation

Results for surface texture, infrared reflectivity, and temporal stability were made from samples prepared by the following. The samples were approximately four inches in diameter and one inch thick. Each substrate was solution heat treated and brought to an appropriate working temper (ie. T7 for 201, T5 for 713, and T52 for 771). The substrates were stabilized against further dimensional changes by subjecting the substrates to a three-times stabilization thermal cycle. This stabilization cycle was from -100 degrees F to 325 degrees F at a rate not exceeding 15 degrees F per minute. Approximately 0.030 on an inch was then conventionally machined from those surfaces to be diamond flycut. The s[illegible]rates were then diamond machined on Rank Pneumo MSG-500 flycutter under the conditions l[illegible]d in table 3.

machine:	Rank Pneumo MSG-500
spindle speed:	3000 rpm
finish slide speed:	2.0 ipm
finish depth of cut:	0.0001 in
flycutter diameter:	12.0 in
coolant:	cyclo-paraffin mineral spirits
diamond tool:	RPI N200KJ 2.5 degree top rake 5.0 degree clearance 0.200 in tool tip radius

Table 3 - Diamond Machining Conditions

Surface Texture

Figure 2 shows a surface texture comparison for a 201 cast substrate as compared to a 6061 wrought substrate. Measurements of surface finish from many 201, 713, 771 cast alloy substrates have displayed comparable surface texture results to the 6061 wrought alloy. Averages of surface texture Ra (arithmetic averages) from samples of these alloys measured on a Rank Taylor Hobson Form Talysurf (contact technique) are shown in table 4.

Alloy	Mean Arithmetic Averages (Angstroms)
201 cast	66
6061 wrought	76
771 cast	84
713 cast	97

Table 4 - Alloy vs. Mean Arithmetic Averages

Although the range of surface textures within each material samples was as large as the total spread between the materials, it was clear that comparable results were obtained. Measurements of the samples by optical non-contact techniques yielded a significantly larger spread of data. This resulted from the restrictive scan length used by the optical technique. For the measurement of a material with discreet grain boundaries, such as aluminum alloys, it is essential to have the scan length be a significant number of grain boundaries for the surface texture measurement to be representative of the surface. Although it is yet to be proved, it is suspected that the correlation between surface finish and material depends on the percentage of non-diamond machinable alloying constituents contained in the alloy.

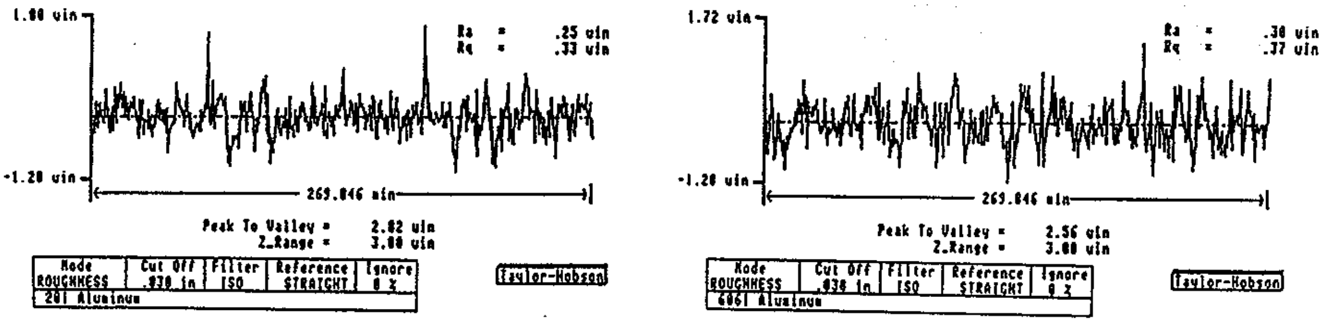


Figure 2 - Surface Texture

Infrared Reflectivity

Figure 3 shows a graph of the averaged infrared reflectivity of diamond machined 201 cast alloy, diamond machined 6061 wrought alloy, and pure aluminum deposited on a polished glass substrate in the 3 to 6 micron spectral region. The data presented here is the average of several samples measured on three separate IR spectrophotometers. Error bands of up to one percent should be included on the graph to reflect the actual spread of data.

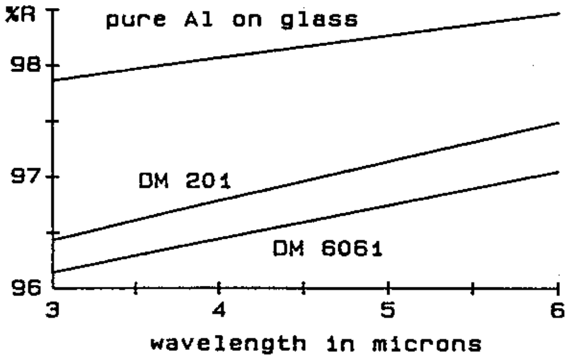
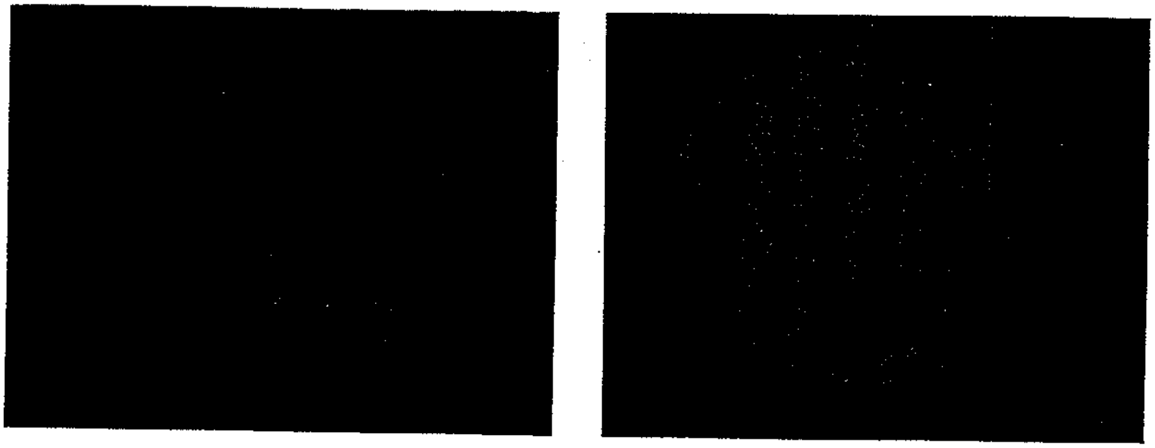


Figure 3 - Infrared Reflectivity for Al Alloys between 3-6µm

Temporal Stability

Figure 4 shows two interferograms of the same 201 cast sample. The four inch diameter substrate was diamond machined in June of 1987. The interferogram on the left was taken minutes after machining and cleaning of the sample. The blank was then stored with the surface unprotected in air at room temperature for six months. The interferogram on the right was taken in December of 1987. The surface geometry change was less than an eighth wave at a wavelength of 632.8 nm. The change was spherical in nature. This may have resulted from the sample not having reached thermal equilibrium during the first testing.

All higher spatial frequency figure errors are virtually identical in the two interferograms. The cast materials appear to exhibit good temporal stability at room temperatures. Specific testing would be required to determine feasibility of use at either elevated or reduced temperatures.



June 1987 December 1987

Figure 4 - Temporal Stability

Conclusion

This study has shown that aluminum castings can be used as diamond machining substrates for the fabrication of optical surfaces. By properly selecting the casting alloys and controlling the casting process comparable diamond machining results to those obtained with the 6061 wrought alloy can be produced.

Acknowledgments

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