Rapidly solidified aluminium for optical applications

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ABSTRACT

This paper present the results of a diamond turning study of a rapidly solidified aluminium 6061 alloy grade, known as RSA6061. It is shown that this small grain material can be diamond turned to smaller roughness values than standard AA6061 aluminium grades. Also, the results are nearly as good as nickel plated surfaces, but the RSA6061 has the advantage that no additional production steps are needed and that no bi-metallic bending or delamination can occur in a thermally changing environment, e.g. when cooling to cryogenic temperature. Therefore, RSA6061 is a good material for optical applications in the visual spectrum.

Keywords: Diamond turning, surface roughness, aluminium, rapidly solidified aluminium, small grain size, optics

1. INTRODUCTION

In space and ground-based astronomy applications aluminium AA6061 is very often the preferred material. One of the reasons for choosing this material is its high specific stiffness and good thermal properties. Also, historically a lot of data has been gathered for this material; choosing this material does not require any new certification trajectories, which keeps the costs low for using this material in space applications.

For stability of the optical system, both mechanical and thermal, AA6061 is often chosen for the reflective optics as well. The choice of a proper manufacturing method, e.g. aluminium mirrors and aluminium mountings, can increase the accuracy of the system, because they have the same thermal expansion coefficient.

Commercially available AA6061 can be diamond turned to surface roughness values of approximately 5-8 nm. For the infrared spectral range this is adequate, but not for the visual spectral range. This becomes clear from the equation for total integrated scatter (TIS). TIS is dependent on surface roughness value Rq and used wavelength[1].

$$TIS = \left(\frac{4\pi\, Rq}{\lambda} \right)^2 \qquad for\ Rq << \lambda \tag{1}$$

Using 300 nm as the shortest visual wavelength, it can be calculated that the Rq value should be smaller than 2.4 nm to have an intensity loss of less than 1% for a mirror. Single-point diamond turning (SPDT) of commercially available AA6061 cannot produce such low surface roughness values. The standard AA6061 is a polycrystalline material with differences in crystallographic orientation. These differences in crystallographic orientations cause differences in hardness and shear incompatibilities between neighboring grains; these are a cause for grain scale roughening, which is observed as the typical “orange peel” surface topography [2]. Having smaller grains would be beneficial.

When low surface roughnesses are required, the aluminium mirrors get AlumniPlated (plating of high purity aluminium) and subsequently diamond turned again to reach smaller Rq values (2-4 nm) [3]. An disadvantage of the AlumniPlate material is that it is relatively soft. Chip removal needs to be very good and cleaning of the diamond turned mirror is very difficult due to the softness of the AlumniPlate.

Another possibility for low surface roughness is the application of a nickel coating that can be diamond turned to roughness values of approximately 1-2 nm. A disadvantage of the nickel plating is the bi-metallic bending that may occur for low temperature applications. This originates from its large difference in thermal expansion from aluminium (13-14.5 for nickel versus 23.6 for AA6061). AlumniPlate is less bothered by this, since its coefficient of thermal

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expansion (24.4) is very close to AA6061 [3]. The benefit that nickel has over AlumniPlate is its hardness that makes it more scratch resistant and better polishable.

Another disadvantage that these platings have is that additional production steps are needed, namely the application of the additional coating after the workpiece surface was diamond turned to its required shape, and next a new diamond turning sequence to reach the final surface roughness and workpiece shape in the plated layer. This increases throughput times.

An interesting method for improving the diamond turnability of aluminium alloys and to circumvent the application of expensive and vulnerable platings is to refine the microstructure of the aluminium alloys. The use of a new production technology for the standard AA6061 alloy is highly interesting. This paper describes the applicability of a new and very good alternative for the standard AA6061 aluminium that is always used in space and ground-based astronomy applications: a rapidly solidified aluminium 6061 grade, called RSA6061, developed by RSP Technology for TNO Science and Industry. This material can be diamond turned to low Rq surface roughness values of approximately 2 nm, making additional platings no longer necessary, which leads to decreasing costs and throughput times.

This paper first presents some backgrounds of rapidly solidified aluminium and next the diamond turnability of conventional aluminium, nickel plated aluminium and rapidly solidified aluminium are presented. Then some applications in which the rapidly solidified aluminium is used are presented, ending with some conclusions.

2. RAPIDLY SOLIDIFIED ALUMINIUM

Rapid solidification can in general be used to improve the mechanical properties of the alloy [4 - 6] by a) extension of the solid solubility to give solute strengthening and precipitate strengthening, b) refinement of the grain size of the matrix and other constituents to give fine grain strengthening and c) formation of new meta-stable phases.

Qualitatively the best rapid solidification process is melt spinning [4], rendering the highest cooling rate of 10^6 K/s and as a result giving the finest microstructure. The general production route is to drop a fine stream of molten aluminium alloy onto a fast rotating copper wheel. The fine ribbon produced in a fraction of a second with a thickness of 20-100 μm is chopped to flakes. This material must be consolidated in order to create an internally coherent and strong material. This is done by compacting, degassing and hot-pressing, hot-isostatic-pressing (HIP) and/or extrusion into bar [5]. The alloy is applied in the form of billet, extruded bar or forged material.

The typical composition of RSA6061 and standard AA6061 aluminium alloy is given in Table 1. Notice from this table that the composition and mechanical behaviour of standard AA6061 can differ very much per supplier because of the wide boundaries accepted for an AA6061 alloy. The RSA6061 has much higher tolerance on its composition, as can be seen from the table.

Table 1: Typical composition of RSA6061 and "standard" AA6061 aluminium.

Wt%	**Si**	**Fe**	**Mg**	**Cu**	**Zn**	**Cr**	**Mn**	**Zr**	**Ti**
RSA-6061	0.6	0.3	1.0	0.3	0.0	0.2	0.1	0.05	0.1
AA6061 specification AMS-QQ-A-200/8	0.4-0.8	0.0-0.7	0.8-1.2	0.15-0.4	0.0-0.25	0.04-0.35	0.0-0.15	0.0-0.05	0.0-0.15

The microstructure of conventional AA6061 is well documented [7 - 8]. It consists of light gray iron related particles of general composition - $(Fe,Mn,Cr)_3SiAl_{12}$ and $(Fe,Mn,Cr)_2Si_2Al_9$ - together with dark Mg_2Si particles which differ in shape and distribution from the iron related particles. The Fe related particles show a sharper edged form whereas Mg_2Si are rounded particles. The control of these particles in terms of size and distribution is of importance to properties like strength, compressibility and surface finish. These particles of which the iron related particles are in the majority, are aligned in the extrusion direction and will show up at the machined surface. The mechanical behaviour of the iron related particles (and the Mg_2Si particles too) is brittle, so they can break on compression of the material [8 – 9] and most probably break under diamond machining and flycutting operations where shear and compressive deformations are present [10]. It was assumed that by reduction of the size of these brittle particles the surface roughness would be improved, which indeed will be shown in this paper.

Because the RSA6061 is rapidly solidified material, its microstructure looks different from the standard AA6061 grade. The microstructure seen with optical microscopy is shown in Figure 1 with left the microstructure of RSA6061 and right the microstructure of conventional AA6061 alloy. The much finer structure of the precipitated phases in the melt-spun and consolidated alloy RSA6061 is clearly visible. The RSA6061 material is available in T6 and T651 conditions. The hardness is 105 HB maximum, which is higher than for the conventional alloy (95 HB). The dimensions of the largest light gray particles in the microstructure of the conventional alloy are in the range 10-20 µm, for the RSA-6061 alloy in the 1 µm range and below. Also the dimension of the Mg_2Si particles is strongly reduced. These particles show up in RSA6061 with the largest size (darkest, black spots).

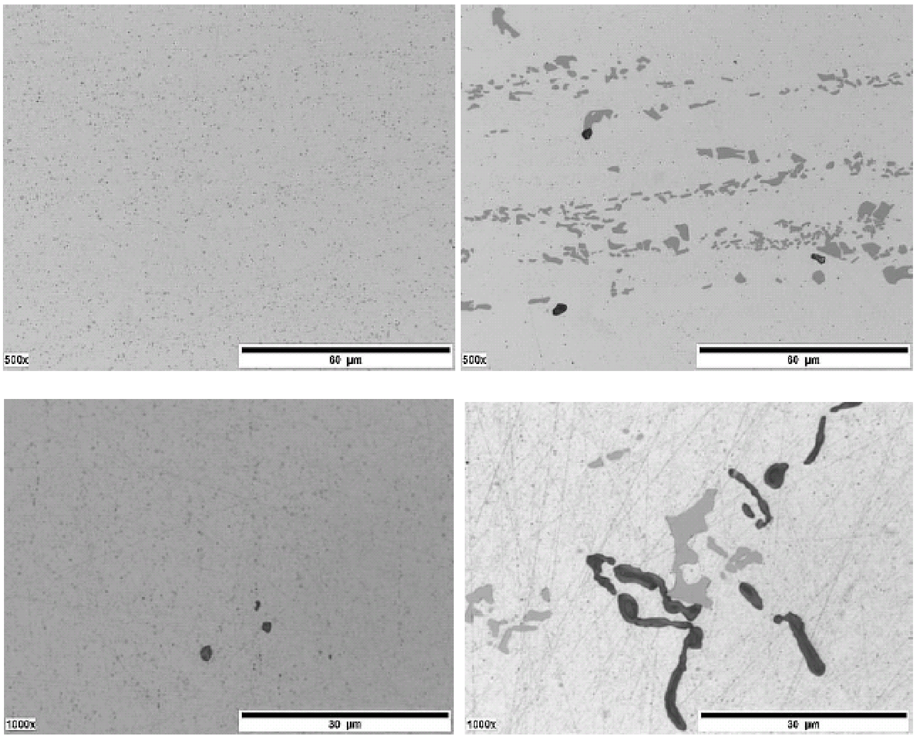


Figure 1: The microstructure of RSA-6061 (left) compared to conventional AA6061 at 500x magnification (above) and at 1000x magnification (below).

3. DIAMOND TURNABILITY

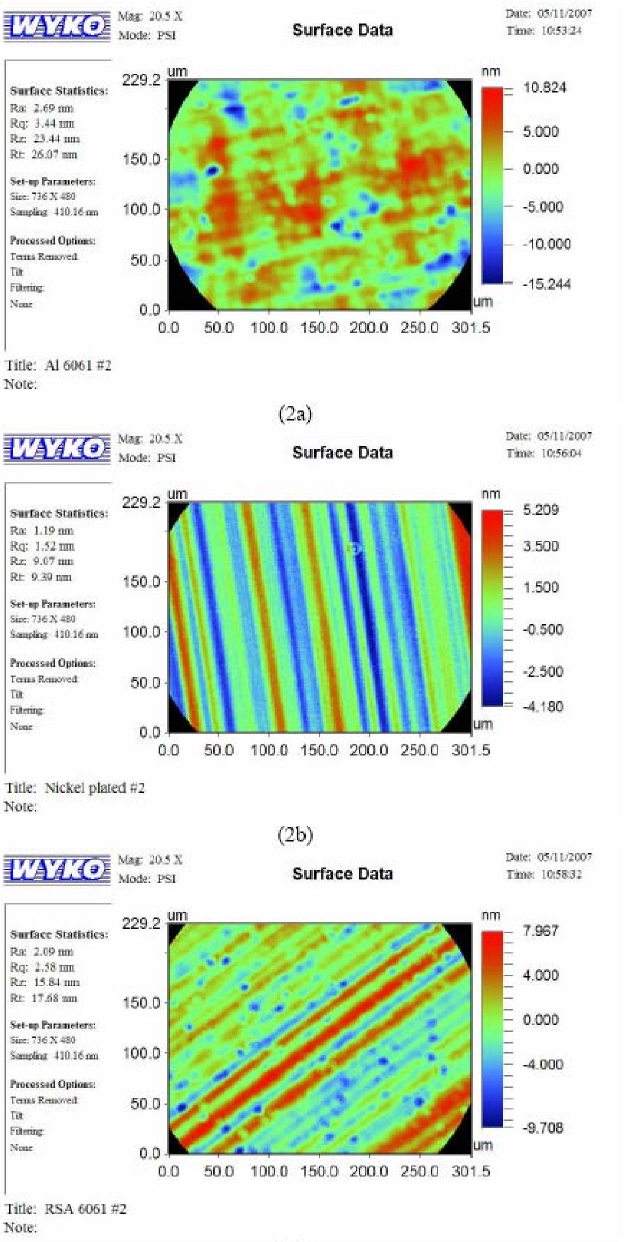
The diamond turnability of conventional AA6061 aluminium alloy, nickel plated and melt-spun RSA6061 aluminium alloy samples is investigated here. Flat samples (diameter 40 mm) were diamond turned on a Precitech Nanoform 350. All samples were diamond turned with a tool nose radius 0.5 mm with zero rake angle, a rotational speed of 3000 rpm, feed rate 5 mm/min and depth of cut 5 µm. Also, a coolant was applied. Table 2 presents the surface roughness values that were measured using a Wyko RST500 profilometer with phase shifting interferometry.

Table 2: Surface roughness values after diamond turning, showing the average value and the standard deviation between parentheses.

	AA 6061	**Ni plated**	**RSA 6061**
Rq / nm	3.8 (0.5)	1.7 (0.3)	2.3 (0.3)
Rz / nm	39.5 (8.9)	27.3 (6.8)	26.5 (5.4)

Looking at the Rq values it can be concluded that nickel can be diamond turned to the best surface roughness values. RSA 6061 scores well too, and has a value below the previously stated 2.4 nm from equation 1 for less than 1% intensity loss by scatter.

The surface structure of the diamond turned surfaces is shown in Figures 2a, 2b and 2c. In nickel and RSA6061 the diamond turning marks can be seen clearly, indicating that the roughness is largely ascribed to the used diamond turning conditions. For AA6061 the final surface roughness is largely determined by the material's crystal structure. The nickel has one benefit over the aluminium grades here. It has a higher hardness value facilitating its polishing behaviour making it possible to reach even lower roughness values more easily. Also, polishing of the nickel plated surface may be needed to remove the diamond turning marks that may lead to unwanted diffraction effects. For the AA6061 this may be of less concern due to the more random structure of the crystal structure left on the surface after diamond turning.



WYKO Mag: 20.5 X Mode: PSI

Surface Data

Date: 05/11/2007 Time: 10:53:24

Surface Statistics:
Ra: 2.69 nm
Rq: 3.44 nm
Rz: 23.44 nm
Rt: 26.07 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 410.16 nm

Processed Options:
Terms Removed:
Tilt
Filtering:
None

Title: Al 6061 #2
Note:

(2a)

WYKO Mag: 20.5 X Mode: PSI

Surface Data

Date: 05/11/2007 Time: 10:56:04

Surface Statistics:
Ra: 1.19 nm
Rq: 1.52 nm
Rz: 9.07 nm
Rt: 9.30 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 410.16 nm

Processed Options:
Terms Removed:
Tilt
Filtering:
None

Title: Nickel plated #2
Note:

(2b)

WYKO Mag: 20.5 X Mode: PSI

Surface Data

Date: 05/11/2007 Time: 10:58:32

Surface Statistics:
Ra: 2.09 nm
Rq: 2.58 nm
Rz: 15.84 nm
Rt: 17.68 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 410.16 nm

Processed Options:
Terms Removed:
Tilt
Filtering:
None

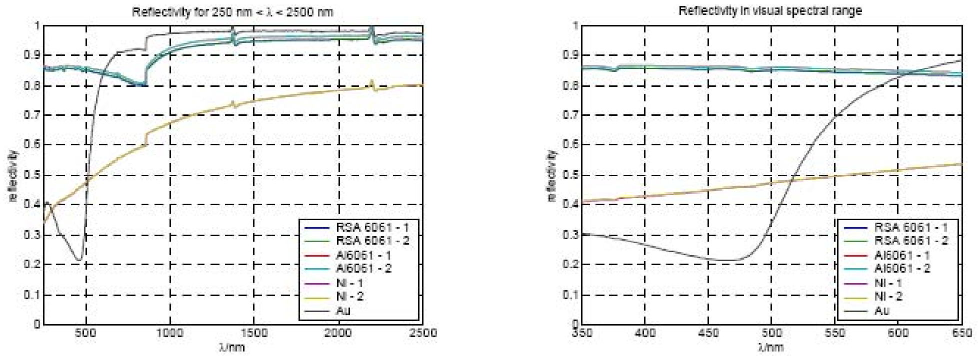
Title: RSA 6061 #2
Note:

(2c)

Figure 2: Surface structures of diamond turned "standard" AA6061 (a), nickel plating (b), and rapidly solidified RSA6061 (c). In nickel and RSA6061 the diamond turning marks can be clearly seen indicating that the roughness is largely attributed to the used diamond turning conditions. For AA6061 the final surface roughness is largely determined by the material's crystal structure.

3.1 Reflectivity

All diamond turned samples were tested for their reflectivity. This was done using a PerkinElmer Lambda 950. For each material two samples were tested. Notice that these results are material characteristics and should not be coupled to equation 1 for the total integrated scatter. Besides the aluminium and the nickel samples a gold coated sample was tested as well. The results are shown in Figure 3.



(a) (b)

Figure 3: Reflectivity measurements from 280 nm to 2500 nm; at the right a detail of the visual spectrum 350 nm to 650 nm. The order of the lines (top-down) in the left graph at a wavelength of 1500 nm is: Au (97%), AA6061 (95%), RSA6061(94%) and Ni (75%).

It can be seen in the left of Figure 3 that all curves have some disturbances in their overall trend, at 860 nm, 1400 nm and 2200 nm. This can be ascribed to detector switches of the used spectrometer. Looking at the curves in the overall spectrum and also to the visual spectrum, the following can be concluded:

1. AA6061 and RSA6061 have the same reflectivity over the measured spectrum (only 1% difference, which can be a measurement error).
2. Even for aluminium with a very high reflectivity value the application of a gold coating is a good option to increase the reflectivity in the (near) infrared region. Gold has the highest reflectivity of the measured materials in that range. However, for the visual range gold coatings are not a good alternative.
3. Although nickel coatings can be diamond turned to RMS roughness values of 1-2 nm, its intrinsic reflectance is very bad compared to aluminium. Certainly for the visual spectral range, the reflectivity is approximately half that of aluminium. This is a very important factor to take into account for optical systems that contain a lot of mirrors.

4. APPLICATIONS

We demonstrate two optical applications that successfully applied the small grain rapidly solidified RSP aluminium grade.

4.1 Star Separator M10 mirror

TNO Science and Industry develops for the Very Large Telescope (VLT), owned by the European Southern Observatory ESO, in Chili the *Star Separator*. Figure 4 shows the cross-section of the M10 mirror that is used in the Star Separator. The M10 mirror has a diameter of 50 mm and consists of two spherical surfaces (radius of curvature approximately 743 mm). The two spherical surfaces coincide at the top line of the workpiece. The Star Separator should be able to look simultaneously to a bright star and a weak star that are close to each other. The light of the bright star is used for determining the wavefront errors introduced by the turbulence in the earth's atmosphere. This signal is used for (nearly) real-time compensation of the weak star's signal.

Looking at the cross-section of the M10 mirror, it can be seen that the top edge needs to be sharp. To be able to separate the light of the weak star from the bright star the edge should not be wider than 30 µm. Polishing trials on nickel plated workpieces showed that it was not possible to make this workpiece with the given tolerance of the top edge. The main reason for that was round-off occurring at the edges during polishing.

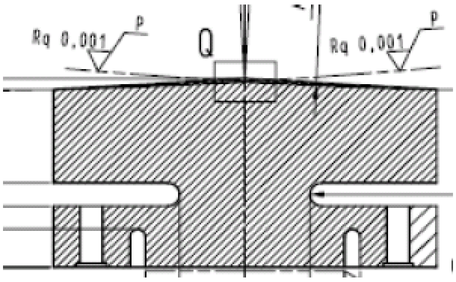


Figure 4: Cross-section of the M10 mirror of the Star Separator. The top edge should be less than 30 µm wide in order to separate the light from a bright and weak star that are close to each other.

To be able to make the M10 mirror with the sharp edge and a surface roughness as low as possible TNO used RSA6061. This material was diamond turned on TNO's Nanoform 350. Using this material and diamond turning we were able to make the top edge less than 3 µm wide. Figure 5 shows a measurement of the top edge measured with a Wyko RST500 profilometer. Furthermore, the workpiece had an Rq surface roughness in the range of 2-3 nm.

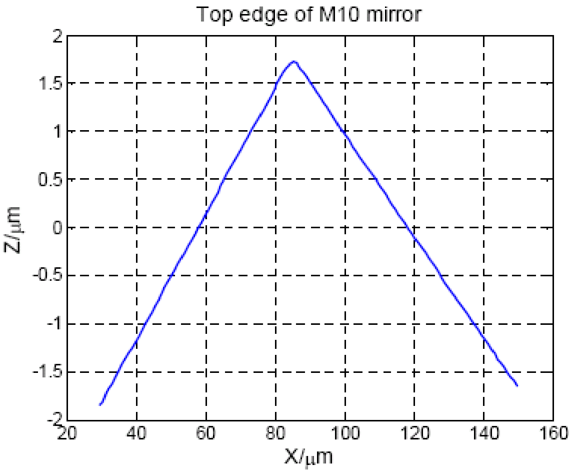


Figure 5: Measurement of the diamond turned M10 mirror. Using the RSA6061 aluminium alloy a surface roughness in the range of 2-3 nm was reached and the top edge was less than 3 µm wide.

4.2 BepiColombo baffle vane

The next example is from a manufacturing study for a baffle vane for ESA's BepiColombo mission that is to be launched in 2013. This example clearly shows the progress that has been reached in the processing capabilities of the RSA6061. Initially only extruded rods with a diameter of 60-90 mm were possible that could be cut to workpieces. Nowadays, large forged workpieces of small grain melt-spun RSA6061 are possible. This example shows a workpiece with a diameter of nearly 250 mm.

The BepiColombo mission has as goal to do research on Mercury's evolution, surface state, geological structure, atmosphere and magnetic field, and to test Einstein's relativity theory. Because of Mercury's close position to the sun, the BepiColombo instruments have to endure a lot of radiation, knowing direct radiation from the sun, indirect radiation from the surface and infrared radiation, but also the high temperatures at Mercury. To protect the instruments from too much radiation, a special baffle is required that reflects more than 93% of the radiation. The geometry of this baffle is defined by the Stavroudis concept [11 - 12], which is known as the most suitable concept to achieve a high rejection performance. The baffle consists of more than 10 separate vanes that have a complex geometry. TNO worked on the manufacturability of the most complex vane: the geometry is rotational symmetric, but the shape consist of a ellipsoidal ($Z = \sqrt{A - BX^2}$) and a hyberboloidal surface ($Z = \sqrt{CX^2 + D}$).

Figure 6a shows two segments taken from a diamond turned solid ring we used for coating testing purposes. Where the two curves meet, a sharp corner is required and therefore diamond turning was chosen. Using a large forged RSA6061 aluminium workpiece, we were able to diamond turn a light-weight, 1 mm thin-walled baffle vane, see Figure 6b. The Rq roughness was in the order of 3 nm.

(a)

(b)

Figure 6: Results of the diamond turned baffle vane for the Bepi Colombo mission. The right figure shows the thin-walled (1 mm thick) baffle segment with a diameter of approximately 250 mm.

5. CONCLUSIONS

RSA6061 is a very promising material for optical applications for the visual spectral range since it can be diamond turned to very small Rq roughness values, approximately 2-3 nm, which is lower than for standard AA6061 alloys. Also, these surface roughness values are as good or nearly as good as AlumniPlate and nickel plated optics. However, application of the RSA6061 material has some big advantages over Alumniplate and/or nickel plated optics:

1. Reduction of production steps is possible, thus leading to decreasing costs and throughput time
2. RSA6061 has the same coefficient of thermal expansion as AA6061, so no bi-metallic effects can occur upon cooling in low temperature applications.
3. The RSA6061 has a higher hardness than AlumniPlate facilitating its cleanability.
4. The RSA6061 has a much higher reflectivity value than nickel plating.

Furthermore, the ongoing improvements in the production process of RSA6061 currently enable the use of larger workpieces that can be diamond turned very well as was show in the applications section. Based on these findings we think that the RSA6061 is a very useful material for optical applications.

ACKNOWLEDGEMENTS

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