DIAMOND TURNING AND POLISHING TESTS ON NEW RSP ALUMINIUM ALLOYS

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ABSTRACT

For years now conventional aluminium 6061 T6 has widely been used for mirrors in astronomical instruments, being diamond turned or since a few years also being optically polished. This allows the development of optical systems that can be tested and operated at any temperature, without being affected by CTE effects. Using traditional aluminium the manufacturing methods could in some cases not deliver the required surface shape, accuracy and roughness due to the increasing demands from optical systems. Over the last few years RSP Technology developed a new series of aluminium alloys for several applications, produced with a Rapid Solidification Process. Both on a macroscopic and microscopic level these new aluminium alloys have different material characteristics compared to the traditional aluminium alloys. TNO and NOVA-ASTRON have performed diamond turning and polishing tests on these new aluminium alloys. This paper presents results of several diamond turning and polishing tests obtained over the last year and show the potential of these new alloys with surface roughness values of 1 nm on RSA 6061 and RSA 708 acquired with both diamond turning and polishing.

Keywords: RSP alloys, diamond turning, polishing, rapid solidified aluminium, melt spun aluminium, surface roughness

1. INTRODUCTION

1.1 Back ground

Single Point Diamond Machining (SPDM) of aluminium optics has progressed dramatically over the past decade. Currently, by use of this technology high quality optics can be manufactured with unique aspherical shapes that are compliant with the strict customer requirements. Unique to the state-of-the-art SPDM is the capability to achieve aspherical surfaces with a micro-roughness of a few nanometers. High accuracy in surface finishing reduces surface scattering to a level acceptable for optical systems operating in the visible region of the spectrum, while this technology was in the past confined to infrared applications. Recent experiences [1],[2] have shown that the surface roughness can greatly be improved by using amorphous material alloys obtained by Rapid Solidification Processing (RSP). The combination of diamond turning for (steep) aspheric optics and low surface roughness of rapidly solidified aluminium is an enabler for the manufacturing of compact reflective telescopes with low F# and large FOV making it possible to build very compact telescopes for both panchromatic and multispectral optical instruments.

1.2 Rapid solidification processing

Melt spinning is a rapid solidification technique for producing alloys with the highest cooling rates possible, up to 10^6 K/s, providing ultra-fine and homogeneous microstructures. Figure 1 shows the different processing steps of the rapid solidification processing. Firstly the alloy needs to be prepared using melting and different alloying elements. Next, the melt is poured through a small nozzle onto a rotating copper wheel, creating a rapidly solidified ribbon. This ribbon is chopped to flakes and collected in a vessel. After that, the flakes are degassed and subjected to hot isostatic pressure (HIP) processing to create a consolidated material. Principally, billet sizes of 1 m diameter can be prepared. If necessary or required, the billets can be extruded or forged to different dimensions.

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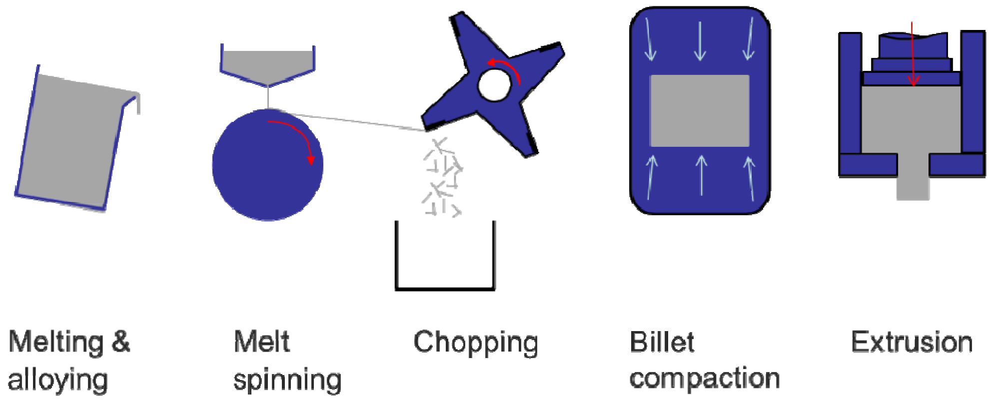


Figure 1: Processing steps in Rapid Solidification Processing.

2. SINGLE POINT DIAMOND TURNING

In a study for the European Space Agency (ESA) TNO investigated the possibilities for using rapidly solidified aluminium (RSA) for diamond turned mirrors. This study focused on achieving the best material processing and diamond turning settings for achieving minimum surface roughness.

2.1 Assessment of standard, non-optimized, diamond turning results

The study of minimizing the surface roughness focused on two types of commercially available rapidly solidified aluminium (RSA): RSA-6061 and RSA-905. The RSA-6061 is a rapidly solidified aluminium with a composition that is within the specifications of the conventional AA6061 alloys. The RSA-905 alloy is a so-called "second generation" aluminium alloy that can only be manufactured using melt spinning technology. It is a dispersion hardened alloy. In contrast to the RSA-6061, the RSA-905 cannot be heat-treated and is only available in an "as extruded" or annealed quality. Both alloys are characterized by their very fine microstructure [1,2]. In first instance different materials (i.e. RSA-6061 and RSA-905), different batches, with different chemical compositions and heat treatments were compared. Furthermore, the difference between billet and extruded bar was investigated for its diamond turnability. The main differences that were investigated are shown in Table 1.

Table 1: Used workpieces, identifications and variations of the tested workpieces.

Change	Identification	Description	Mechanical treatment	Extrusion ratio	Fe	Mg/Si	Remarks
Alloying component							
1	1-5020-7	RSA6061-T6'	extrusion	14,06	0,33	1,94	Fe-high / Mg/Si-relatively high
2	2-8002-6	RSA6061-T6'	billet	1,00	0,15	1,97	Fe-low / Mg/Si-relatively high / no extrusion!
3	3-7016-4	RSA6061-T6'	extrusion	7,91	0,11	2,22	Fe-low / Mg/Si-high
4	4-9000-6	RSA6061-T6'	extrusion	4,18	0,17	1,61	Fe-red-low / Mg/Si-low
13	13-9004-4	RSA6061-T65	extrusion	6,44	0,09	2,16	T651, stretched (2-3%) after T6
Thermal treatment							
5	5-7016-4	RSA6061	extrusion	7,91	0,11	2,22	Extra high precipitation hardening temperatur
6	6-7016-4	RSA6061	extrusion	7,91	0,11	2,22	Soft quench
7	7-7016-4	RSA6061	extrusion	7,91	0,11	2,22	Soft quench and high annealing temperature
8	8-7016-4	RSA6061	extrusion	7,91	0,11	2,22	high annealing temperature
9	9-7016-4	RSA6061-T6	extrusion	7,91	0,11	2,22	most standard T6
Alloy							
10	10-8003HF	RSA905	billet	1,00			
11	11-8003HF	RSA905	extrusion	6,44			
12	12-HT2006	AA6061-T651	extrusion				extrusion, T651, see certificate for details

All samples were diamond turned using the same conditions, i.e. same rotational speed, feed rate, depth of cut, spray mist settings, same machine etc. This is necessary to show the influence of material, concentration or heat treatment only. The following conditions were used:

- Spindle speed: 2500 rpm
- Depth of cut: 4 µm
- Feed rate: 2 mm/min (0.8 µm/rev)
- Machine: Precitech 700A
- Synthetic spray mist

For each material/grade, three samples were machined. Samples were 60 or 80 mm in diameter. Since many samples had to be diamond turned the effect of tool life could become visible in the results . To prevent this one sample of each batch was diamond turned. Next the reverse order was used for diamond turning the second sample, and in the third sequence a random order was applied. No trend was found for the influence of tool wear.

Figure 2 shows the surface roughness values for the chosen standard, non-optimized, diamond turning settings. Each bar is the average of the roughness of three different workpieces. The following can be seen in this graph:

Conventional AA6061 can be diamond turned to approximately 5 nm Rq surface roughness. Furthermore, RSA-6061 and RSA-905 behave similarly with respect to achievable surface roughness with these settings. Also, billets seem to have a slightly higher surface roughness values after diamond turning than the extruded bars. It will be shown later that with proper diamond turning condition, this will not be true.

Heat treatments of RSA-6061 can have some effect on the achievable surface roughness. Scanning Electron Microscopy by Aalto University has shown that the chosen heat treatment settings influence the amount and size of Mg_2Si precipitates.

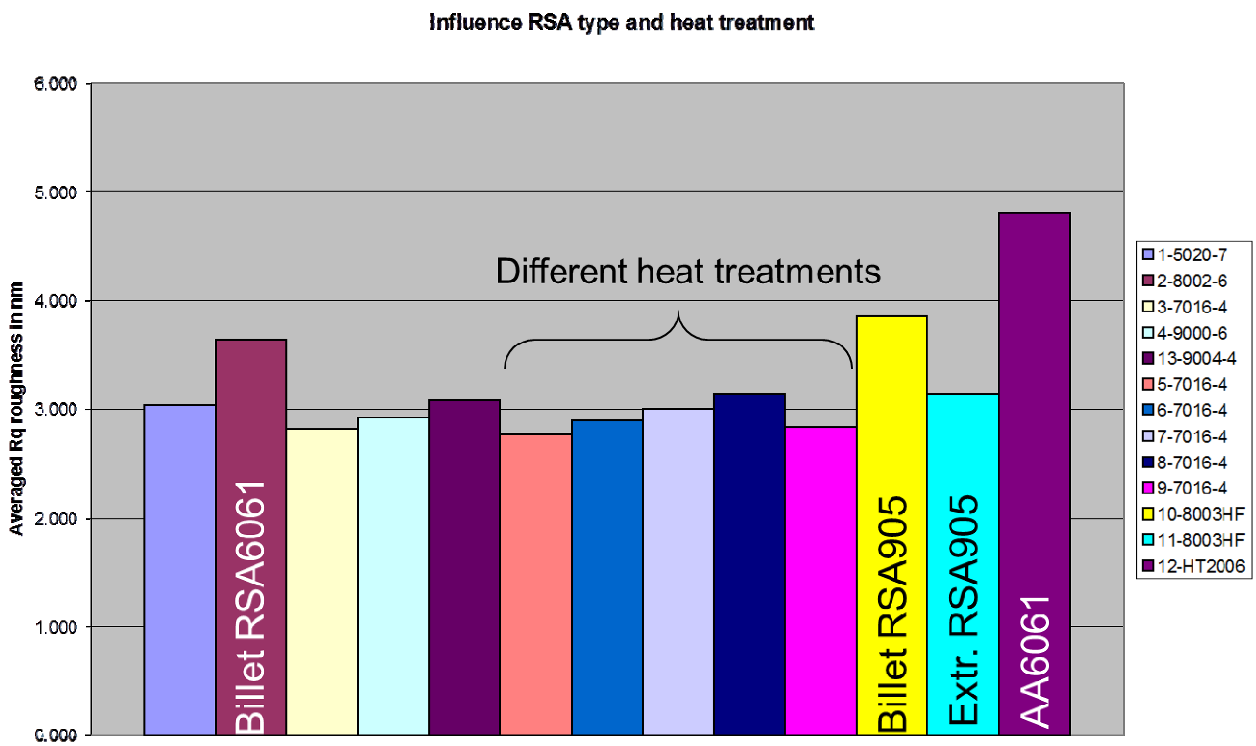


Figure 2: Surface roughness values of different materials, different batches RSA-6061 (see legend and Table 1), billets vs. extruded bars and conventional AA6061. All shown for a standard, non-optimized, diamond turning setting.

Plotting the differences in chemical composition of RSA-6061 showed no relation with respect to Mg/Si ratio and no relation with iron (Fe) content in the composition. However, a relation was found with hardness, but this was coupled to the applied heat treatment procedure.

2.2 Design of Experiments

In the previous section the result of non-optimized diamond turning settings were shown. However, it would be interesting to determine what factors influence the diamond turning result the most with respect to achievable surface roughness. For that purpose, a Design of Experiments (DOE) was used. In this DOE, the following factors were investigated using a "low/high" study: machine, operator, tool wear (expressed as "sharpness" in the results), spindle speed, feed rate, diamond crystal orientation, tool nose radius, plano/spherical workpiece, lubricant application pressure, lubricant quantity, rake angle of the tool and material (RSA-6061 vs. RSA-905).

In a DOE of 48 experiments it was possible to investigate the dominant main factors of the diamond turning process of RSA. These 48 experiments consist of 24 low and 24 high settings for each of the factors. The outcome that was investigated was the Rq surface roughness value. This value was the average of an automated profilometer measurement (Wyko NT9300) of 26 random points over the surface.

Figure 3 shows the absolute effect of the factors, and which ones are "statistically relevant". The absolute effect shows the difference between the average roughness of the low and the high setting. With reference to Figure 3, this means that the choice between one or the other machine means an improvement of more than 1,25 nm Rq. Furthermore, sharpness meant that a sharp tool needs to be used, and not a "ran in" tool. Also, a rake angle of 0° gives the best results. These are all "fixed" settings, i.e. one can choose the best machine, tool configuration and sharpness of the tool. However, spindle speed and feed rate can be tuned to achieve an optimum result.

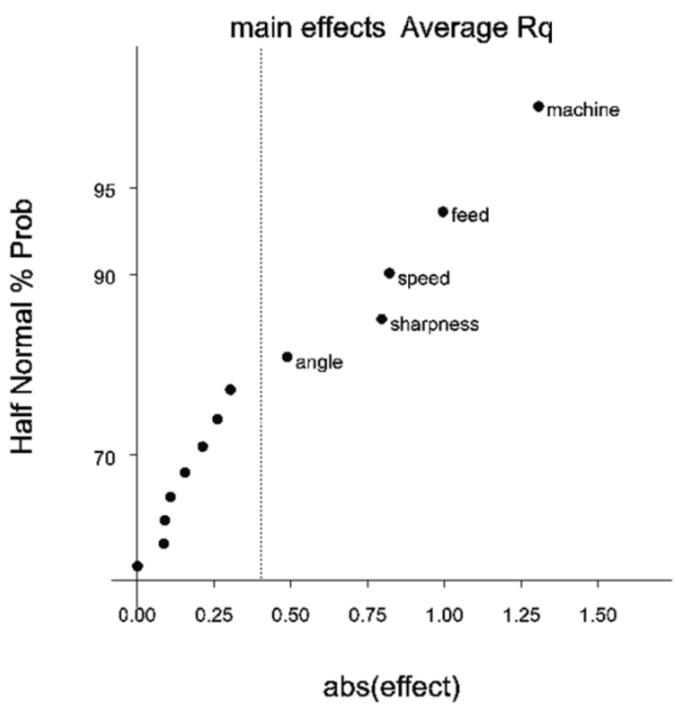


Figure 3: Absolute effect of the investigated main factors of the DOE. Machine choice, tool wear and rake angle are "fixed" factors, where the best can be chosen. Spindle speed and feed rate can be tuned.

Principally, the tuning of the spindle speed S (rev/min) and feed rate F (mm/min) resulted in a simple relationship, which appeared independent for the investigated spindle speed range of 1000 to 4000 rpm, to obtain a minimum surface roughness:

$$F/S = 1.3 \mu m/rev$$

Equation 1: Definition of feed rate to achieve minimum surface roughness on rapidly solidified aluminium alloys.

2.3 Optimized diamond turning results

Using the optimal feed rate, plano samples were used to show the optimum diamond turning results. The same samples that were used in the assessment phase, so principally the workpieces that were used to obtain Figure 1. However, the RSA-6061 were now heat treated in such a way to obtain the smallest and least Mg_2Si precipitates. The RSA-905 samples were not treated differently.

Figure 4 shows the optimum achievable surface roughness values on two different RSA alloys. The following can be observed:

1. Proper heat treatment of RSA-6061 and optimum diamond turning conditions can yield surface roughness values of Rq 1 nm.
2. The non-heat treatable RSA-905 can be diamond turned to approximately 2 nm surface roughness.
3. There is no difference in achievable surface roughness values between billet and extruded bar. This makes it possible to make large diameter mirrors from billets and still achieve 1 nm surface roughness.
4. Tool wear or "Run in" of the tool is not an issue. Seven workpieces were diamond turned with the same tool (total length of cut approximately 35 km).
5. Batch variations of the RSA-6061 have no influence on the achievable surface roughness value of 1 nm.

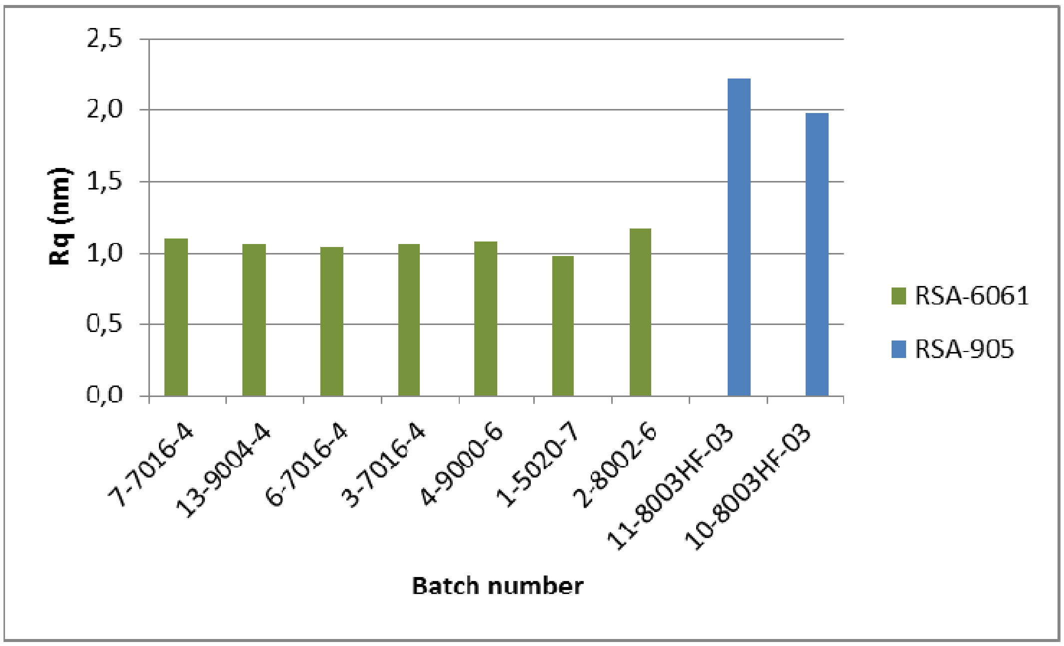


Figure 4: Optimized surface roughness values of diamond turned RSA. Same samples as in Figure 1 were used. RSA-6061 was optimally heat treated and diamond turned. RSA-905 is non-heat treatable, so only optimum diamond turning conditions were used. Interesting to see is that 2-8002-6 and 10-8003HF-03 are billets and that similar surface roughness values can be obtained as on extruded bar.

Figure 5 shows a typical result that was achieved with the optimized diamond turning conditions. Different RSA-6061 batches were used, but all optimally heat-treated. The image is of the 5^{th} workpiece. More than 10 workpieces were diamond turned to 1 nm surface roughness.

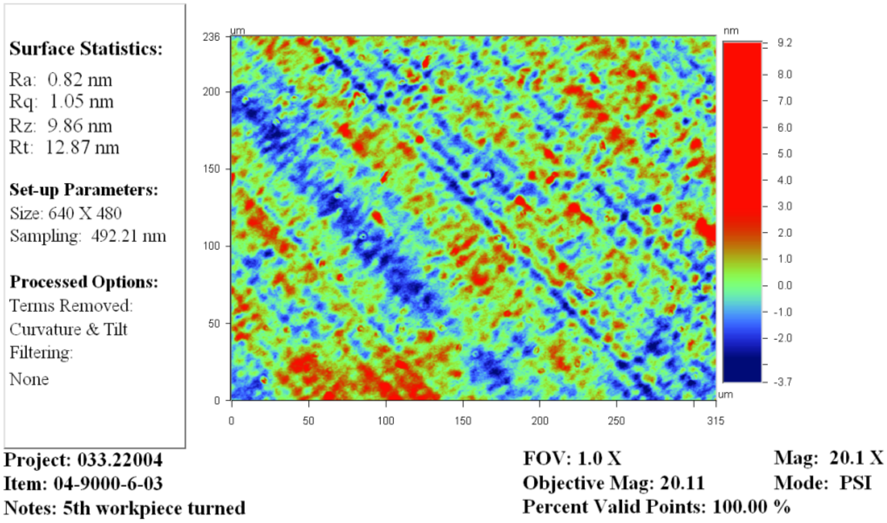


Figure 5: Diamond turned surface of RSA-6061, using optimized heat treatment and diamond turning conditions. Multiple workpieces (from different production batches) were diamond turned to 1 nm Rq surface roughness.

3. POLISHING

3.1 Conventional AA6061

During the last ten years a large amount of mirrors have been made from this material for instruments like Visir, MIRI and X-Shooter, which are all (Near-) Infrared Instruments. For X-Shooter, mirrors up to 300 mm diameter have been produced with P-V surface accuracies up to λ/4 @ 633 nm over the entire surface. Surface roughness for the X-Shooter mirrors was around 1-1.5 nm Ra. All mirrors showed a bluish haze and visually small scratches could be detected. However, they were not a problem considering the operational wavelength of the instrument. In 2004 ASTRON achieved for the first time a roughness of less than 1 nm Ra on a polished 20 mm sample.

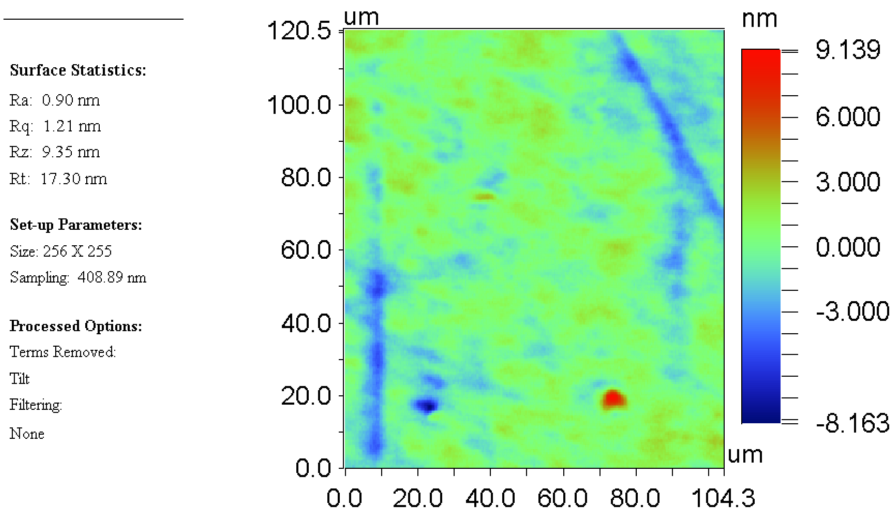


Figure 6: Polished AA6061. The conventional alloy can be polished to 1 nm Rq.

ASTRON polished its largest mirror for the X-shooter instrument. This mirror, M7, has an optical diameter of 280 mm and is made from conventional AA6061. It took four weeks to obtain sufficient cosmetic surface quality. AA6061 scratches easily and often displays a greyish or bluish haze. When too much pressure is applied during polishing, material will be pulled out of the surface creating scratches and pits. Best results have been obtained with low pressure and a diamond slurry on a Lapmaster. The use of dense polishing pads (felt) improves the clarity of the surface, but it will introduce considerably more 'orange-peel' leading to a deteriorated surface texture.

3.2 Rapidly solidified aluminium

Rapidly solidified aluminium has a more homogenous microstructure. It is therefore expected that less material impurities can break out during polishing. With optical instrumentation in mind three types of RSA were selected for polishing trials: RSA 6061, RSA 708 and RSA 905. The next table summarizes the chemical compositions that were used in this research.

Polishing tests were performed on rectangular mirrors of 100 mm x 70 mm. All RSA sample materials were made from extruded material and the polishing plane was lying in the long axis of the extrusion. Polishing was performed on a Lapmaster.

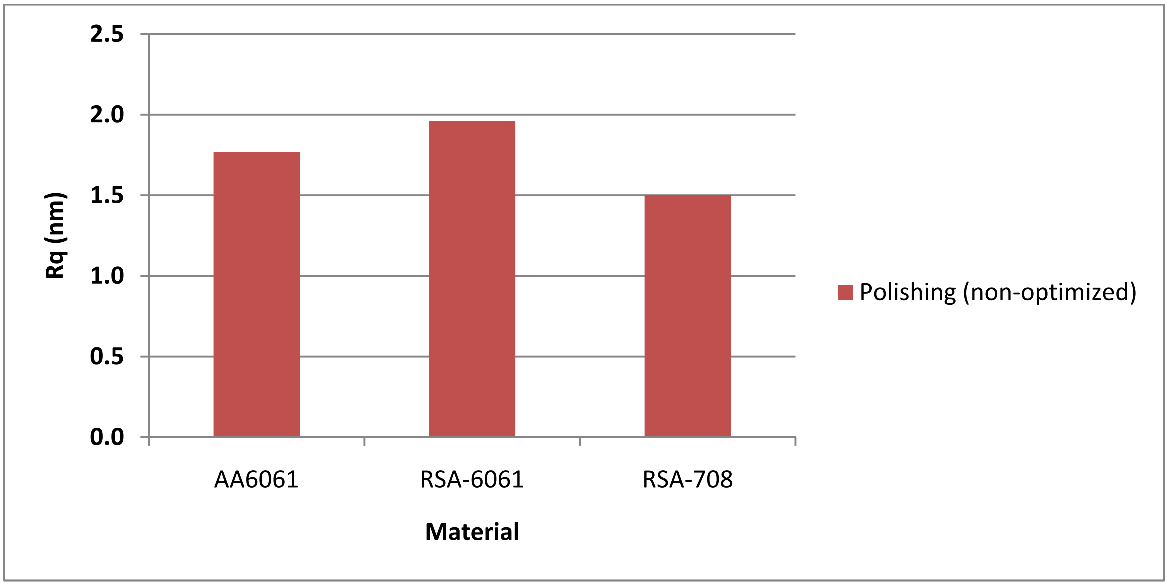
Although it is known that the RSA-905 can be polished very well when the mirror surface is lying perpendicular to the axis of extrusion, the RSA-905 samples polished in this investigation resulted in bad surfaces, which was attributed to the polishing plane lying along the extrusion direction. Since this is typically not the plane that mirrors are made from, the data is omitted in this publication. Unfortunately no other measurement data of a "normal mirror plane" made from RSA-905 bar was present at the time of writing. This will be part of further research and will be presented in a next publication.

As the polishing tests are very preliminary it is expected that the results will improve considerably over the next few years when the process is optimized for the specific characteristics of these materials. Figure 6 shows the results of the test samples for non-optimized polishing settings.

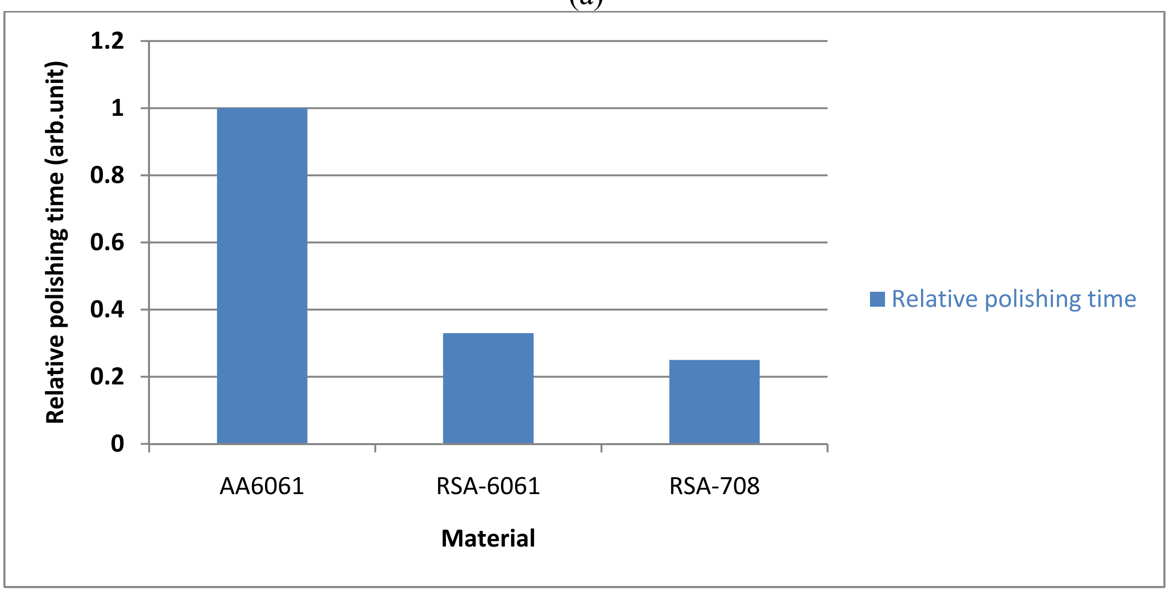
For AA6061 a "regular" surface roughness of 1.8 nm is shown. It can be seen that this first polishing trial resulted in a very similar surface roughness value of RSA-6061 and RSA-708. For RSA-6061 a mirror was made after the tests. This mirror was polished to a surface roughness of 1.6 nm. This is not as good as the data shown in Figure 6, but the polishing times are greatly reduced with the RSA alloys, see Figure 6(b). The mirror has a surface structure as shown in Figure 8. Further process optimization is foreseen to improve this number to less than 1 nm.

Table 2: Chemical composition of the used RSAs.

	Composition (wt%)									
	Al	Fe	Cu	Si	Mg	Mn	Zr	Mo	Zn	Ni
RSA-6061	balanced		0,3	0,5	1,1					
RSA-708	balanced		1,1		2,3				11	
RSA-905	balanced	2,5	2,5			1	0,8	0,8		5



(a)



(b)

Figure 7: (a) Surface roughness values (Rq) for different RSA-materials after the non-optimized polishing process vs. AA6061. (b) shows the relative times that are needed to achieve these surface roughness values, showing a significant decrease in polishing time to achieve <2 nm surface roughness.

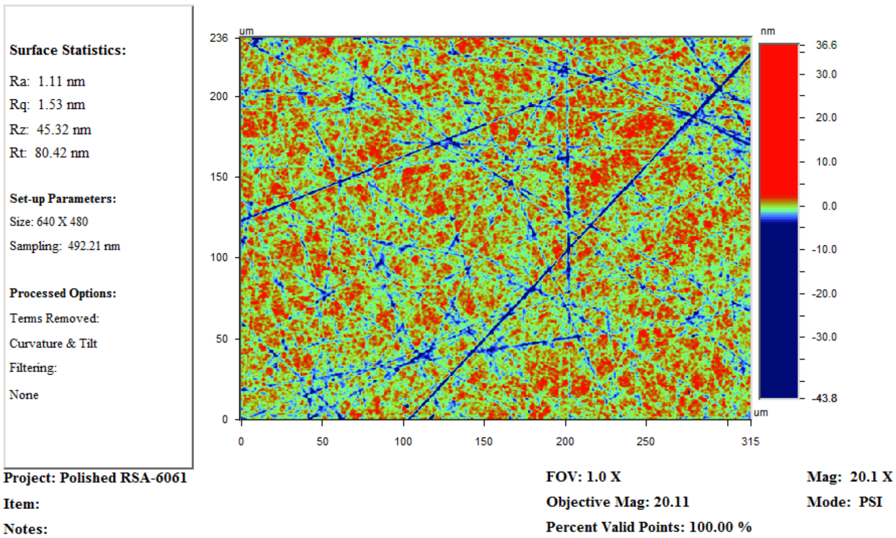


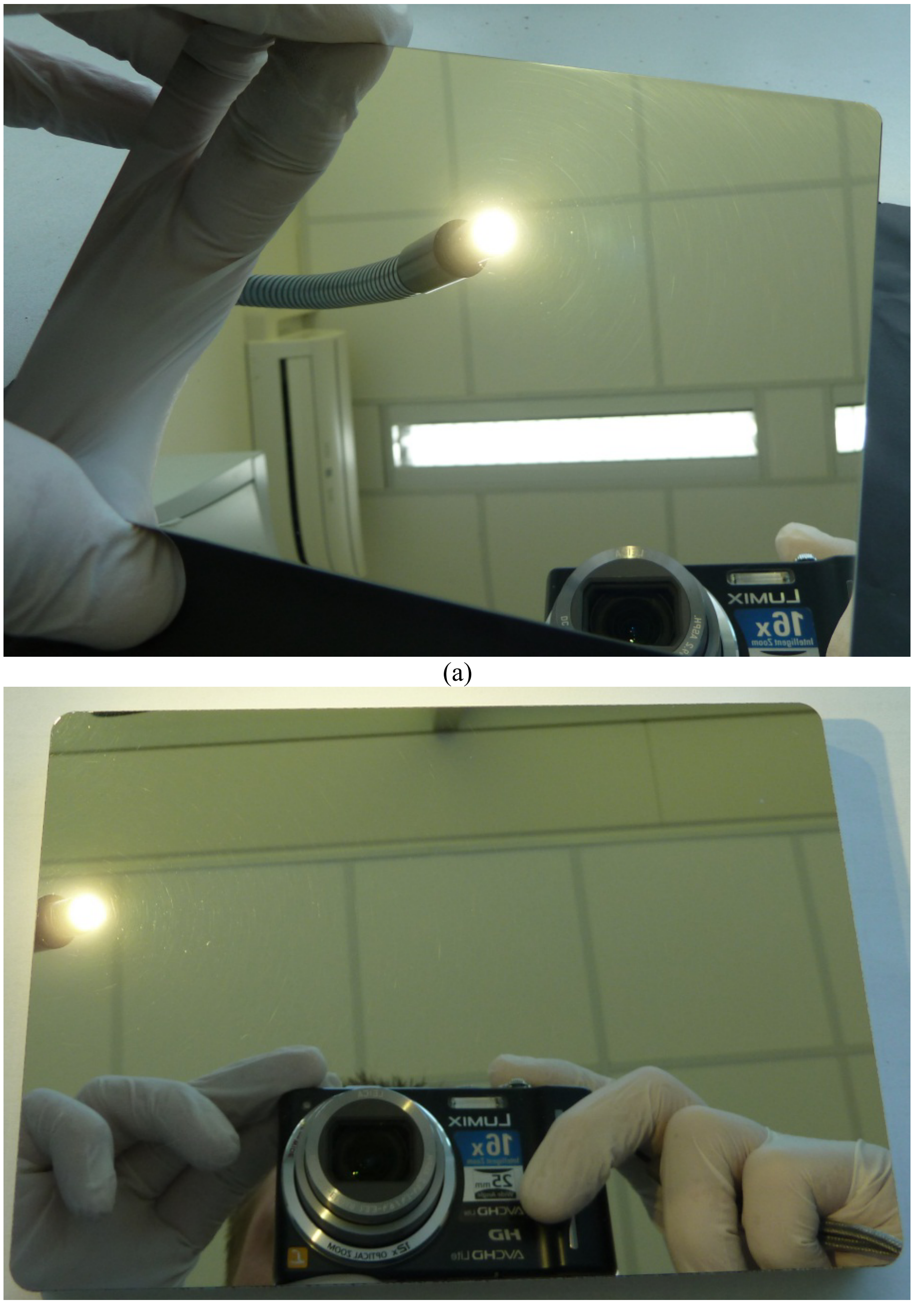
Figure 8: Polished surface of an RSA-6061 mirror, showing a 1.5 nm Rq surface roughness value.

Visually, the appearance of RSA-6061, see Figure 9(a), is quite similar compared to conventional AA6061. The limited available time for the polishing test might have had a negative influence on the results since a considerably better surface roughness was expected with this material. The expectation is that an improved, optimized polishing process will result in a surface roughness of less than 1 nm Rq.

Looking at the rectangular plate of RSA-708, Figure 7(b), a bright surface can be seen. However, some small scratches can be seen in the surface, but it is expected that these can be polished away if more time is spent on these samples. The latter was confirmed by recent polishing activities of ASTRON on a 200 mm diameter disc of RSA-708. Initially it was polished on the Lapmaster, but due to the relatively high weight of the blank no good surface could be obtained. However, when polished TOT (Tool On Top) a brightly polished surface appeared, which was most likely the result of the reduced surface pressure. In fact, it seemed to be the best surface ever made at ASTRON. Only two days were needed to obtain this surface quality. Although not objective, but based on earlier polishing experiments we estimate a surface roughness <1 nm Ra. Although very small, scratches were still visible using a light source. The surface quality seems sufficient for applications at visual wavelengths. Unfortunately no surface roughness measurements have been performed yet. The best results were achieved using a soft pitch with diamond slurry. Whenever starting a new polishing session it seemed unavoidable to have a scratched surface, the more time in between sessions the worse it got. This is probably caused by oxidation of either small metal particles in the pitch lap, or oxidation of the surface of the mirror itself. A polishing optimization is needed.

4. OUTLOOK AND CONCLUSIONS

Rapidly solidified aluminium (RSA) has a very homogeneous microstructure due to its unique manufacturing method. When the RSA-6061 alloy is applied in diamond turning to manufacture mirrors, very good results can be achieved with respect to surface roughness. Rq values of 1 nm have been achieved on multiple batches during diamond turning. This makes the material an interesting alternative to diamond turning of Ni-P plating or Alumiplate. These platings always introduce extra delivery times and risks of delamination. Because of the low surface roughness value, RSA-6061 is an enabler for direct diamond turning of steep aspherical and freeform optics for opto-mechanical instrumentation without the need of post-polishing. No difference between billet and extruded bar has been observed when optimized heat treatment and diamond turning settings were applied. This makes it possible to make large optics from the RSA-6061 as well. Large optics up to 1 meter can be made from billet material. Using the optimized heat treatment found in this research, RSP Technology is currently working on material qualification for the European Space Agency.



(a)

(b)

Figure 9: Polished RSA-6061 (a) and RSA-708 (b).

Polishing of rapidly solidified aluminium shows benefits in the speed of achieving a low surface roughness. A reduction in polishing time to 1/3rd of conventional AA6061 is possible for the RSA-6061 alloy, and even more improvement for the RSA-708. In general, polished aluminium can exhibit good results as far as surface shape accuracy is concerned on flat and spherical surfaces. The quality of surface roughness (and cosmetic quality) depends greatly on the alloy and on the used parameters of the polishing process. In general it is known that aluminium is hard to polish: obtaining a visually scratch-free surface is very difficult and often it shows a bluish haze caused by microscopic scratches. However, surface quality of most polished alloys is good enough for NIR and IR instrumentation. For visual and UV purposes RSA seems to be very promising, especially RSA-6061 and RSA-708. The polishing processes for these RSA alloys will be further improved to achieve <1 nm Rq values, making it applicable for visual and UV instrumentation.

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