euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

Benchmarking rapidly solidified aluminium alloys for ultra-precision machining of ultra-violet mirrors and diffractive optical elements

D.A. Rolon[1,2], F. Hölzel[2], J. Kober[1], S. Kühne[1], M. Malcher[1], T.K. Naderi, [1], T. Arnold[2], D. Oberschmidt[1]

[1]*Technishce Universität Berlin, department of Micro and Precision Devices MFG, Germany*
[2]*Leibniz Institute of Surface Engineering (IOM), Germany*

rolon@mfg.tu-berlin.de

Abstract

Only few materials are suited for the manufacturing of diffractive gratings or mirrors designed for the ultra-violet (UV) range. In recent years, research has been undertaken to identify materials capable of supporting microstructures created by ultra-precision machining while possessing the surface roughness required for mirror applications in the UV range. Rapidly solidified aluminium alloys (RSA) have emerged as promising candidates due to their micrometre sized grain and desirable optical properties. Since certain characteristics of common industry-standard alloys limit their use in UV optics, developing new and improved alloys holds significant potential. This paper benchmarks aluminium alloys RSA-6061-T6, RSA-902, RSA-7034-T6, and RSA-501. A series of ultra-precision shaping experiments with facetted single crystal diamond (SCD) tools were conducted to manufacture diffractive grating structures. Flat surfaces were polished to produce optical surfaces. The results obtained through white light interferometry (WLI) and atomic force microscopy (AFM) measurements indicate that RSA-6061-T6, RSA-902, and RSA-501 are promising candidates for mirror applications. Root-mean-square surface roughness Sq < 10 nm during the experiments were achieved. Moreover, besides RSA-501, RSA-7034-T6 is considered a candidate for diffractive optical elements for its capability to support microstructures. WLI measurements indicate that the constrains on achieving low surface roughness in ultra-precision shaping processes are predominantly driven by the size and - to a lesser degree - the composition of precipitates within the material. It is important to highlight, the impact precipitations have on surface formation during cutting. These precipitations due to its mechanical properties result in the random distribution of defects on the surface. Furthermore, flake structures over the RSA-501 and RSA-902 are possible to be observed, however no correlation with defects was found.

RSA-alloys, Mechanical Manufacturing, Ultra-precision machining

1. Introduction

Aluminium alloys have gained in importance for optical system applications in the past years [1-3]. Among their desirable characteristics, mechanical properties like elastic modulus, hardness, density, and, in some cases, the thermal expansion coefficient, are crucial for the application and machinability of these alloys. Naturally, high reflectivity across a broad range of the electromagnetic spectrum including UV, is essential for optical applications. Innovative methods to produce these alloys attract the attention of optical system manufacturers towards materials. For instance: The melt-spinning process has proven to be an effective method to produce the RSA-501 alloy with an average grain size $d_g \leq 1$ µm [2]. The literature shows that the reduced grain size enables achieving optical surfaces with Sq < 10 nm by means of ultra-precision shaping [2]. Literature concerned with inhomogeneities in these alloys' textures and the resultant influence on their machinability is scarce.

The aim of this investigation is to analyse the feasibility of recently developed RSA-902, RSA-6061-T6, RSA-7034-T6, RSA-501 for the manufacturing of optical elements. The T6 heat treatment indicates that the alloy was heat treated and aged at 150 °C to hardened precipitations and increase the mechanical properties of the alloy. In order to give a step forward to find aluminium alloys suitable for further improvement of the surface roughness by means of UP-machining and ion beam etching. The texture of the above-mentioned alloys must be first analysed. The first hypothesis to be tested is the existence of a flake structure generated from the production process of RSA-alloys. Since they may incur in surface damage during cutting. Secondly, the correlation between the flake structure and surface formation during the cutting of mirrors and structured surfaces is examined.

During the melt-spinning process the alloys are rapidly cooled in less than a second, resulting in the formation of thin ribbons. The primary characteristic of this process is its ability to prevent grain growth, thereby generating very fine oversaturated crystals. After solidification, these ribbons are chopped and subjected to hot isostatic pressing (HIP) before being extruded at 300°C [3]. The fine grain structure facilitates smooth surfaces and is of advantage for other finishing processes such as ion beam etching.

For achieving the required surface roughness for UV-applications, aluminium alloy substrates can be machined by ultra-precision machining resulting in a suitable surface quality for ion beam processing. Mechanical polishing process of UP-machined aluminium alloy substrates often results in undesirable form deviations. With ion beam etching no such deviations are created. Ion beam etching is proven to reduce surface roughness [3]. However, the presence of precipitations and inhomogeneities within the alloys and their influence on surface formation during cutting and etching is not discussed conclusively.

In ultra-precision machining with diamond tools, the above-mentioned precipitations can be directly responsible for tool wear. Also, such precipitations are responsible for the formation of voids or pits along the material surface during cutting, limiting the attainable roughness [3]. In ion beam etching processes, such precipitations and polycrystalline grain structures, can be responsible for different etching rates. Therefore, increasing the surface roughness instead of reducing it. Within the realm of ion beam etching, different strategies can be pursued to diminish the influence of the grain orientation by forming a passivation layer using O_2 gas [3]. However, inhomogeneities within the material must be first understood, the defects origin must be found, then a proper method to deal with them can be suggested.

2. Equipment and method

RSA-6061-T6, RSA-902, RSA7034-T6, and RSA-501 were metallographically prepared, considering the extrusion direction. The dimensions of the samples for the analysis are 15 mm x 15 mm x 10 mm, with each sample cut either in the longitudinal or transverse direction. Similar samples, were used for the ultra-precision shaping experiments.

For the ultra-precision shaping experiments, faceted diamond tools with a setting angle $\chi'r = 1°$ were used. The experiments were conducted in a modified machine tool MMC1100 by LT-Ultra technology GmbH, Germany. The cutting strategy used is previously described by Rolon [2] and Steinkopf [4]. The strategy consists of orienting the stepover direction of cutting towards the short grating size. The main reason for using this strategy is its capability to achieve constant cutting conditions and to avoid collisions of the tool with the tip of the blaze structure.

The metallographic preparation was conducted using slurries with abrasive grains ranging from 1 µm ≤ d_g ≤ 3 µm. The alloys were etched using a 10 % concentration of NaOH.

For the electron backscatter diffraction (EBSD) measurement, samples were prepared with a vibration polishing process using diamond grains with d_g = 0.5 µm. Measurements of the prepared samples was performed in a scanning electron microscope DSM 982 GEMINI by Carl Zeiss AG, Germany. For the calculation of grain size, the calliper method provided by the MTEX toolbox in a self-developed script in MATLAB, from MathWorks, USA, was used following the method described by Rolon, et. al. [2]. The etched samples were analysed using a light microscope DM6 by Leica Microsystems GmbH, Germany. Topography measurements from the machining experiments were conducted with a white light interferometer (WLI) Wyko NT1100 by Veeco, USA, and an atomic force microscope (AFM) Nanite by Nanosurf AG, Switzerland.

3. Results

3.1. Polishing

All materials were polished using the same parameters and steps. Figure 1 shows WLI measurements of the surface and Figure 2 the achievable surface roughness measured in 5 different areas over the surface.

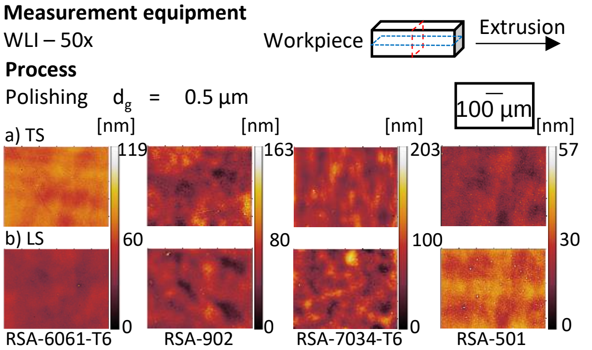

Figure 1. WLI measurement of RSA-6061-T6, RSA-902, RSA-7034-T6, and RSA-501

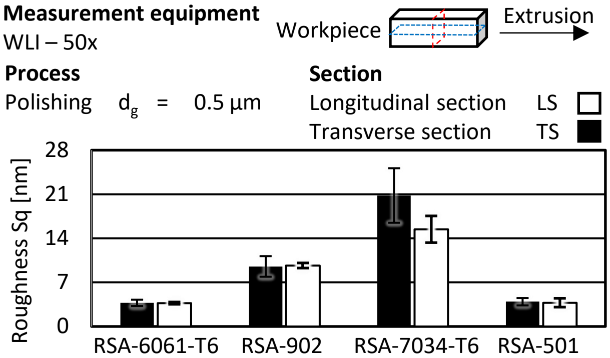

Figure 2. Vibration polishing surfaces of RSA-6061-T6, RSA-902, RSA-7034-T6, and RSA-501

3.2. Texture characterisation of RSA-alloys

By metallographic preparing the above-mentioned alloys, and etching them using NaOH 10% flake structure and precipitation becomes evident. The flake structure indicates areas with different grain sizes or concentration of precipitations. Figure 3 shows the result of the chemical etching using 10% NaOH.

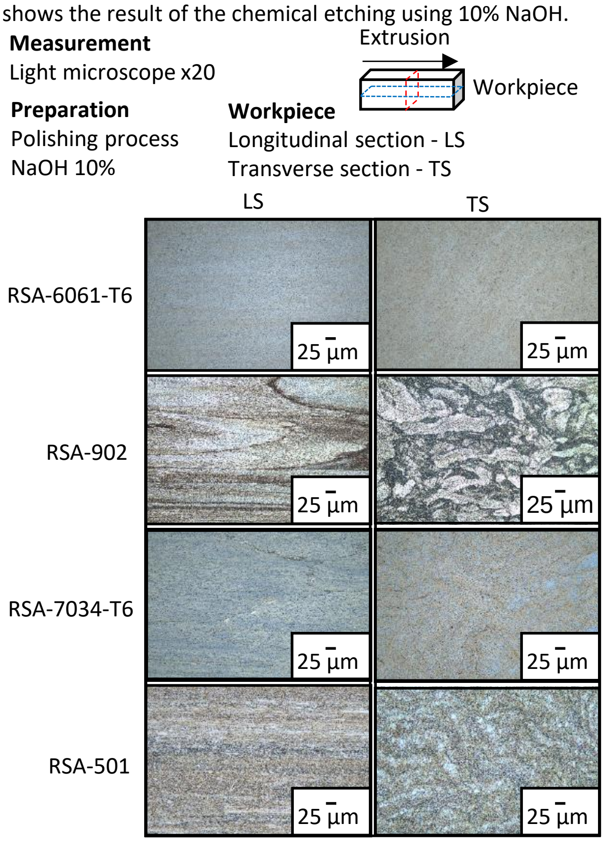

Figure 3. Light microscope measurements of RSA-6061-T6, RSA-902, RSA-7034-T6, RSA-501 regarding the longitudinal and transverse section of each alloy

After preparing the alloy, EBSD measurements were taken and grain sizes of the aluminium phase were measured. Figure 4 shows the EBSD-measurements of RSA-6061-T6, RSA-902. RSA-7034-T6, and RSA-501 along the transversal and longitudinal section. Figure 4 shows the histogram of grain size distribution for each alloy and section. In Table 1 the calculated mean grain size based on the grain distribution provided by the Calliper method of the MTEX MATLAB tool box is presented.

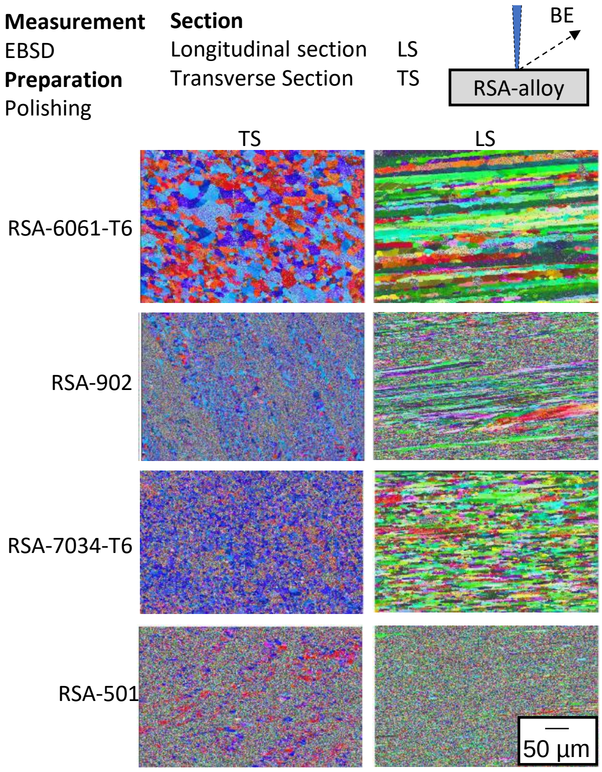

Figure 4. EBSD measurements of RSA-6061-T6, RSA-902, RSA-7034-T6, RSA-501 regarding the longitudinal and transverse section of each alloy.

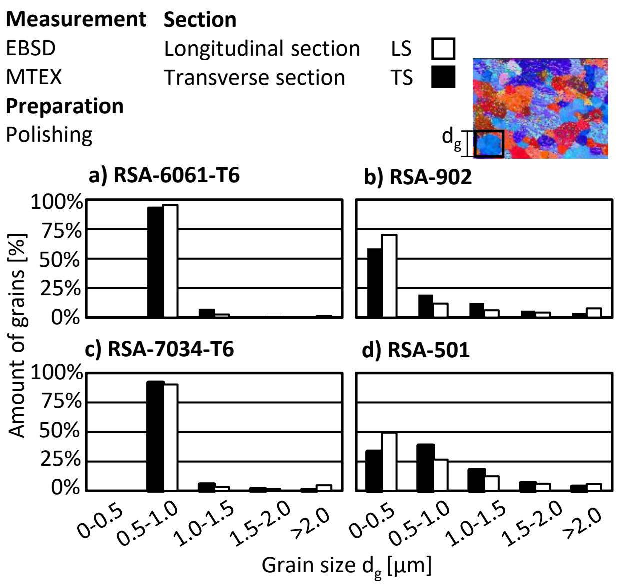

Figure 5. Distribution of grain size along the material texture

Table 1 Average grain size calculation for each alloy

	Average grain size d_g			
Section	RSA-6061 T6 [µm]	RSA-902 [µm]	RSA-7034 T6 [µm]	RSA-501 [µm]
TS	0,80 ± 0,11	0,77 ± 0,88	0,86 ± 0,92	0,90 ± 1,01
LS	1,01 ± 7,18	0,80 ± 2,20	1,22 ± 3,80	1,01 ± 0,90

3.3 Ultra-precision shaping surfaces

Ultra-precision shaping experiments were conducted according to the description in section 2. The only varied variable was the alloy. In this experiment, RSA-6061-T6, RSA,902, RSA-7034-T6, RSA-501 were structured using a facetted single crystal diamond tool. Figure 6a) shows the results obtained within the experiments. Figure 6b) presents the profiles of representative defects of the machined surfaces.

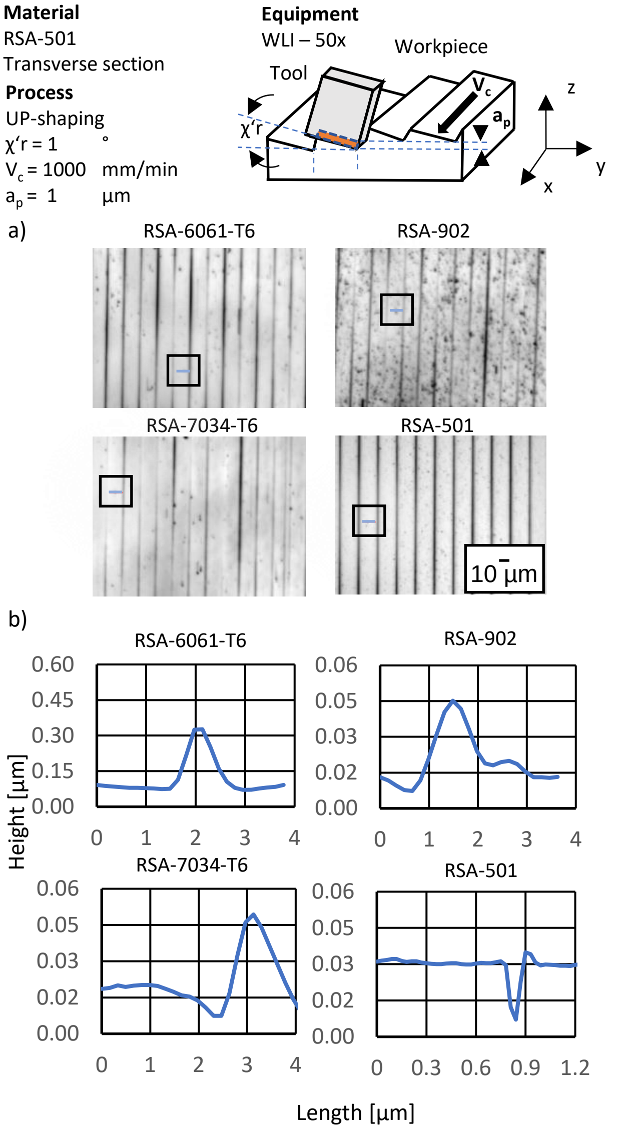

Figure 6.a) Grey scale images of UP-shaped surfaces of the RSA-alloys. **b)** Profile of exemplary defects.

4. Discussion

Analysis of the chemically etched structures in Figure 3 reveals areas with a pattern on the material texture. These patterns are more evident in RSA-902 and RSA-501 and less evident in RSA-6061-T6 and RSA-7034-T6. Furthermore, the shape of these patterns is strongly related to the direction of extrusion. Therefore, such patterns on the material texture are characterized as flake structures. The hypothesis based on this observation is that these structures is formed due to two distinct mechanisms. The first mechanism is the reaction of the etching media with precipitations within the material, implying that the precipitations are concentrated in specific areas. The second possible mechanism considers the crystallization effects following the rapid cooling during the alloy's production. Specifically, during the ribbon formation process, prior to the hot isostatic pressing (HIP). During the production of the alloy, the molten alloy is poured on a rotating cooling copper wheel as illustrated in Figure 7 b). Depending on the pressure and speed of this wheel, ribbons with a specific thickness are rapidly created. The area of the initial contact of the molten alloy with the cooling copper wheel crystallises almost immediately.

It it is proven that the contact area with the wheel has smaller grains compared to the outer region of the ribbon in such rapid cooling processes [5]. What supports these mechanisms is that RSA-6061-T6 and RSA-7034-T6 do not show evident flake structures. The reason could be related to the post process heat treatment T6 on the alloy, in which the alloy is heat treated and aged at 150 °C. Therefore, the grains are allowed again to grow and to be more homogenous on the material texture. While the flake structures may seem not relevant for conventional or micro-machining processes, they are critical in ultra-precision machining. In processes where chip thickness can be in the sub-micrometre range, it is assumed that the non-uniform texture of the material will have different reaction during cutting. Therefore, generating defects over the surface of the material. Investigation concerning the influence of such flakes during cutting are still ongoing. To test this hypothesis, different material batches must be tested and more machining experiments are required.

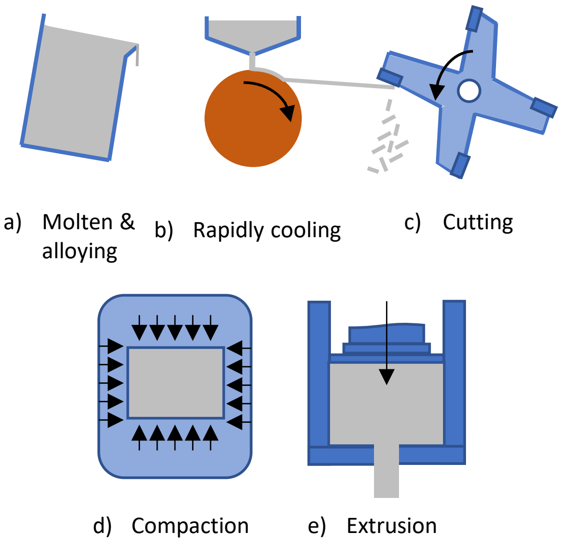

Figure 7. Production process chain of RSA-alloys.

At the polishing experiments, since the abrasive grain trajectory is not conducted in a definable path, it is expected that the cutting process occurs in all possible directions. Therefore, the influence of the achievable surface roughness regarding cutting orientation was not significantly different. The average grain size deviation between transversal and longitudinal direction were not significantly different from another. This experiment indicates the type of surfaces that can be achieved during a mechanical manufacturing process. However, there is still room for improvements of certain surface properties. Especially for RSA-902 further experiments must be conducted in order to assess the influence of the cutting parameters during the polishing process on surface formation.

Ultra-precision shaping experiments with relatively small undeformed chip thickness indicate the possibility to manufacture grating structures using RSA-501, RSA-7034-T6, and, to some extent, RSA-6061-T6. However, the inhomogeneities themselves still present a challenge for the cutting process with facetted diamond tools. Especially precipitations found within the alloys may cause hill-like ruptures. This phenomenon is observed more frequently in RSA-902. Flake structure and surface damage during cutting using facetted diamond tools cannot be correlated yet. However, it is expected that material textures with more concentrated precipitations would result in more defects during material removal. Also, considering the second supposition, areas of increased grain heterogeneity may lead to higher surface roughness by forming a step at the grain's borders. Literature indicates this phenomenon is observed while machining aluminium AA6061-T6 [6].

5. Conclusion

The texture characterization of the investigated alloys reveals insights into potential undesired inhomogeneities within the alloys. Notably, the presence of flake structures and varied grain sizes could be limiting factors in achieving desired surface roughness through mechanical manufacturing processes. However, further experiments are necessary to substantiate this hypothesis.

Alloys developed by RSP Technology are emerging as promising candidates for use in the optical manufacturing industry. Of the optical materials studied, RSA-6061-T6 and RSA-902 demonstrate favourable surface properties for mirror applications. RSA-902 exhibits a higher roughness compared to RSA-6061-T6 and RSA-501, but there is potential for process optimization to enhance its surface property. Particularly in RSA-902, the presence of precipitations limits the attainable surface roughness in ultra-precision shaping processes. Detailed assessments of its precipitations' stoichiometry are needed for optimization. Employing ion beam etching techniques could potentially yield improved surface roughness compared to current results as shown by Hölzel, et al. [3].

In the category of high-strength alloys, RSA-501 stands out as a versatile material suitable not only for structured surfaces but also for mirror manufacturing. Its surface quality is comparable to that of RSA-6061. Additionally, in ultra-precision (UP) shaping processes.

6. Outlook

For further experiments, ribbons prior to the HIP process, and resultant alloys after HIP will be further analysed using the same methods as the ones discussed in this paper. The aim is to correlate grain size to ribbon thickness and its relation to flake structures appearance observed in this paper. This approach will allow the customization of RSA-alloys to improve the surface characteristics of these alloys.

Acknowledgements

The project is funded by the German Research Foundation (DFG) – 452333040. Moreover, the authors acknowledge the contributions of Mr. Roger Senden from RSP Technology for providing the RSA-alloys and technical information about the alloy production.

References

[1] T. Newswander, B. Crowther, G. Gubbels, and R. Senden 2013 *Aluminum alloy AA-6061 and RSA-6061 heat treatment for large mirror applications*, Proc. SPIE 8837, Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, **883704**.

[2] D.A. Rolon, et al. *Suitability of Aluminium RSA-501 for manufacturing diffractive optical elements by shaping processes*. 2023 at 23st International Conference, EUSPEN.

[3] F. Hölzel, et al. 2023. Reactive ion beam smoothing of rapidly solidified aluminum (RSA) 501 surfaces for potential visible and ultraviolet light applications. Surfaces and Interfaces **38,** 102784.

[4] R. Steinkopf, et al. Optimization of diamond machined gratings for low light scattering and highest diffraction efficiencies. 2023 at 23st International Conference, EUSPEN.

[5] F. Palm, R. et al. Scalmalloy® = A Unique High Strength AlMgSc Type MaterialConcept Processed by Innovative Technologies for AerospaceApplications. PM2010 World Congress. PM Aluminiumn and Magnesium 2. 2010-

[6] R. G. Jasinevicius, et al. *Size effects in ultraprecision machining of aluminum alloys: Conventional AA6061-T6 and RSA 6061-T6*. 2021 in Journal of Manufacturing Processes **68**, Part B, 136-157.