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Suitability of aluminium RSA-501 for manufacturing diffractive optical elements by shaping processes

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Abstract

Diffractive gratings are key elements in spectrometers and monochromators, but only a few materials are suitable for producing the required blaze structures. For example, aluminium alloys are commonly used for applications in the visible light spectrum. Ultrafine-grained aluminium alloys, such as rapidly solidified aluminum (RSA)-501, are promising materials for the fabrication of diffraction gratings and are even suitable for use with ultra-violet (UV) light. However, the influence of cutting parameters in the ultra-precision (UP) shaping of RSA-501 by faceted diamond tools remains to be explored. The aim of this publication is to determine not only the optical properties of diffractive gratings of RSA-501, but also the relationship between the machining parameters and surface formation. Machining experiments were used to investigate the effects of variations in rake angle and depth of cut during the ultra-precision shaping process. Scanning electron microscope (SEM), transmission electron microscope (TEM), electron backscatter diffraction (EBSD), and energy dispersive X-ray (EDX) measurements were utilised to analyse the granular structure and precipitates in RSA-501. The material was processed longitudinally and 90° to the extrusion direction to investigate possible anisotropies caused by the extrusion process during fabrication. Chips collected during the machining experiments were ex-situ evaluated. Surfaces of the fabricated samples were topographically investigated using atomic force microscopy (AFM) and white light interferometry (WLI). The measurements indicate differences in granular structure and possible anisotropic behaviour. Precipitates of (Mg, Si), (Fe, Mn) and (Al, Sc, Zr) were possibly detected. Machining experiments showed that the surface quality of the blaze facet structures could be significantly improved by reducing the rake angle and depth of cut. Surface roughnesses of Sq < 6 nm were achieved. Based on these results, RSA-501 can be considered a suitable material for the fabrication of diffraction gratings.

Diffractive gratings, Ultra-precision shaping, RSA-501

1. Introduction

Innovative methods to produce aluminum alloys for a wide range of applications have attracted attention in recent years [1-3]. For instance, meltspinning allows to produce aluminum alloys with very fine grain size of $d_g < 1$ µm. This fine grain structure enhances the mechanical properties such as hardness and stiffness of aluminum alloys. Moreover, it also extends the range of applications to optical elements with very low surface roughness. The reduced grain size allows the material to be machined by ultra-precision diamond processes within an average surface roughness of Sa < 5 nm [4].
After the meltspinning process, ribbons are segmented and submitted to a hot isostatic pressing (HIP) to form billets. Those billets are then extruded to rectangular bars [5]. Due to the extrusion process, the grains of the aluminium alloy are expected to be stretched along the extrusion direction. Therefore, the generated material has anisotropic properties [3].
RSA-501 has been applied in several investigations to manufacture diffractive gratings for spectrometers and as master piece for further replication processes [6]. These diffractive gratings are evaluated not only by its form, but also final surface quality of blaze facet after UP-shaping. Therefore cutting mechanisms has to be fully understood to achieve damage-free blaze facets. Especially, while manufacturing curved gratings as shown in Figure 1. While manufacturing them, the workpiece is displaced along in X or Y axis, while moving the tool within the Z axis. This type of displacement causes a variation of the rake angle along the tool path. Hence, causing different cutting conditions and different surface properties and appearance of defects.

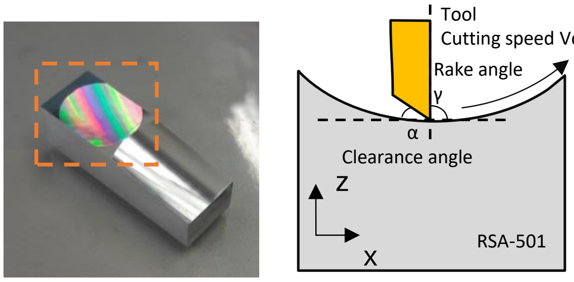

Figure 1 Example of a RSA-501 grating manufactured by UP-shaping process

Inhomogenities regarding the grain structures and precipitates formed during the addition of alloying elements are belived to be the source of the defects detected [1,2]. Therefore, the aim of this paper is to evaluate the cutting mechanism of UP-shaping of diffractive gratings in RSA-501. Since the rake angle γ varies during UP-shaping process of curved diffractive gratings, experiments changing the rake angle from $-20° \leq \gamma \leq 0°$ were conducted. Since the depth of cut a_p is strongly related to the chip section and therefore to the surface formation, investigations aiming at analysing the effects of the variation of the depth of cut for 5.0 µm ≤ a_p ≤ 0.5 µm on the appearance of surface defects were conducted. The tool setting angle $\varkappa'r$ = 1° and lateral feed f = 9 µm were kept constant. Moreover, the limitations of the alloy towards the surface formation regarding stretched grain orientations and precipitations are key elements to be understood. Therefore, the chemical composition, precipitations, and grain deformation were characterized.

2. Equipment and method

RSA-501 raw material was firstly segmented in two types of samples according to the extrusion direction. The first type of samples were cut along the extrusion direction in a shape of 15 mm x 15 mm x 10 mm blocks. The second type investigated was perpendicular to the extrusion direction having the same dimensions. Those samples (Figure 2) were then prepared for chemical analysis and for the UP-shaping experiments.

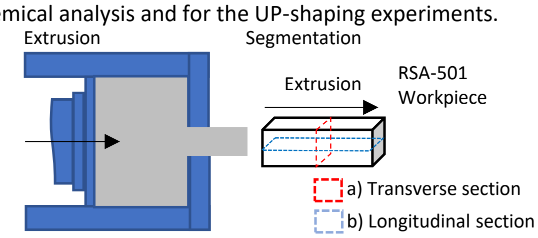

Figure 2 RSA-501 samples segmented according to the extrusion direction

2.1. Workpiece characterization

For the chemical characterization of RSA-501, samples were prepared by fly-cutting and polishing processes. X-ray fluorescence (XRF) spectroscopy measurements were conducted in a SPECTROSCOUT by AMETEK INC., USA. Scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) measurements of chips and the microstructure on the cut sample surfaces were perfomed in a DSM 982 GEMINI by CARL ZEISS AG, Germany. Furthermore, transmission electron microscopy (TEM) analysis of the sample was done in a JEM-ARM300F2 by JEOL LTD., Japan. Also, nanoindentations in the RSA-501 surface were perfomed in order to measure possible anisotropy derived from the production of the raw material.

2.2. UP-shaping experiments

Machining experiments took place in a modified ultra-precision machine-tool LT-Ultra MMC1100 by LT ULTRA-PRECISION TECHNOLOGY GMBH, Germany. RSA-501 samples were first prepared by a UP-flycutting process in order to reach excellent surface finish and plane parallelity. For the experiments a 3-axis shaping process and a faceted diamond tool with adjustable rake angle were utilised.

3. Results

3.1. Characterisation of RSA-501

A XRF measurement roughly confirmed the element composition of RSA-501 that was provided by RSP TECHNOLOGY, Netherlands. However, contaminantations such as Silicon (Si), Iron (Fe), and Copper (Cu) were found within the alloy composition [7]. Table 1 shows the XRF measurement result of a sample of RSA-501. EDX mapping in a TEM indicated the existance of precipitates (Figure 3). Among the alloying elements, contaminants were also found.

Table 1 XRF measurements of a RSA-501 sample

Element mass [%]							
Al	**Mg**	**Mn**	**Zr**	**Sc**	**Fe**	**Cu**	**Si**
93.3	3.5	0.9	0.8	0.9	0.1	<0.1	<0.1

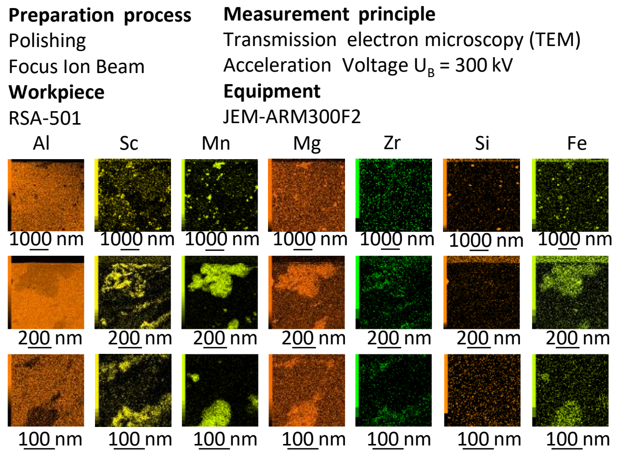

Figure 3 EDX measurements of precipitates of RSA-501 alloy performed in TEM

Samples segmented along and across the extrusion direction were measured using EBSD. Measurements along the extrusion direction present elongated grains. Samples segmented across the extrusion direction present areas with grains of bigger size than the average grain size d_g < 1 µm . Figure 4 shows both sections of RSA-501 according to their extrusion direction.

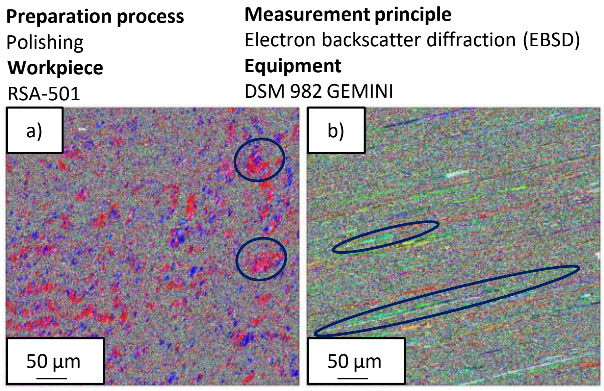

Figure 4 EBSD measurements of a) transverse section (TS) and b) longitudinal section (LS), adapted from [3].

Nanoindentation tests using a berkovich indenter were conducted on the two types of RSA-501 samples prepared by UP-flycutting process. Overall 50 measurements per orientation were analysed and the measurement uncertainties were calculated using a coverage factor k = 2 (Table 2).

Table 2 Results of nanoindentation investigations [3]

Material	**RSA-501**	
Tool	Berkovich Tip	
Preparaion	UP-flycutting	
Load/Unload time	5 s	
Load	10 µN	
Orientation	Longitudinal	Transverse
Reduced E-Module E_r	112.9 ± 1.4 GPa	110.8 ± 2.9 GPa
Hardness H	3.08 ± 0.09 GPa	2.96 ± 0.11 GPa

3.2. Influence of process parameters on appearance of defects

Samples of RSA-501 were prepared by electric discharge machining (EDM) and fixed in the UP-machine tool and prepared for UP-shaping experiments. One possible method to manufacture gratings is to displace two axis (X,Z) without rotation of the tool. By doing so, the rake angle of the tool can be varied from -20°≤ γ ≤ 0° limited by the clearance angle α of the tool. In this study, a tool with a clearance angle α = 5° was used. Therefore the maximum rake angle γ = 0° is recommended

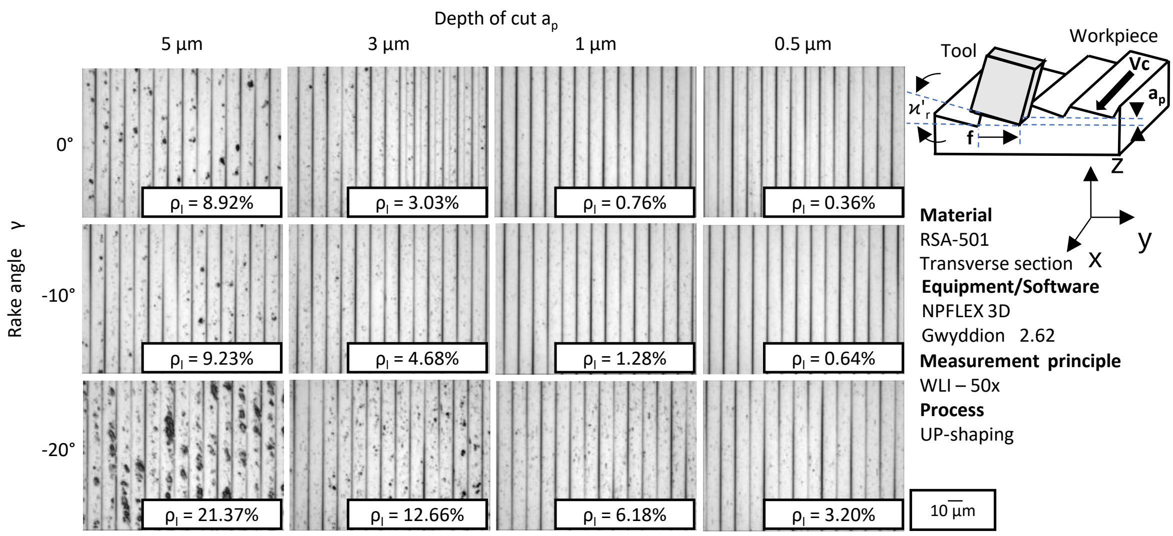

Figure 5 WLI-images of the machined surfaces of each parameter variation and corresponding percentage of defects

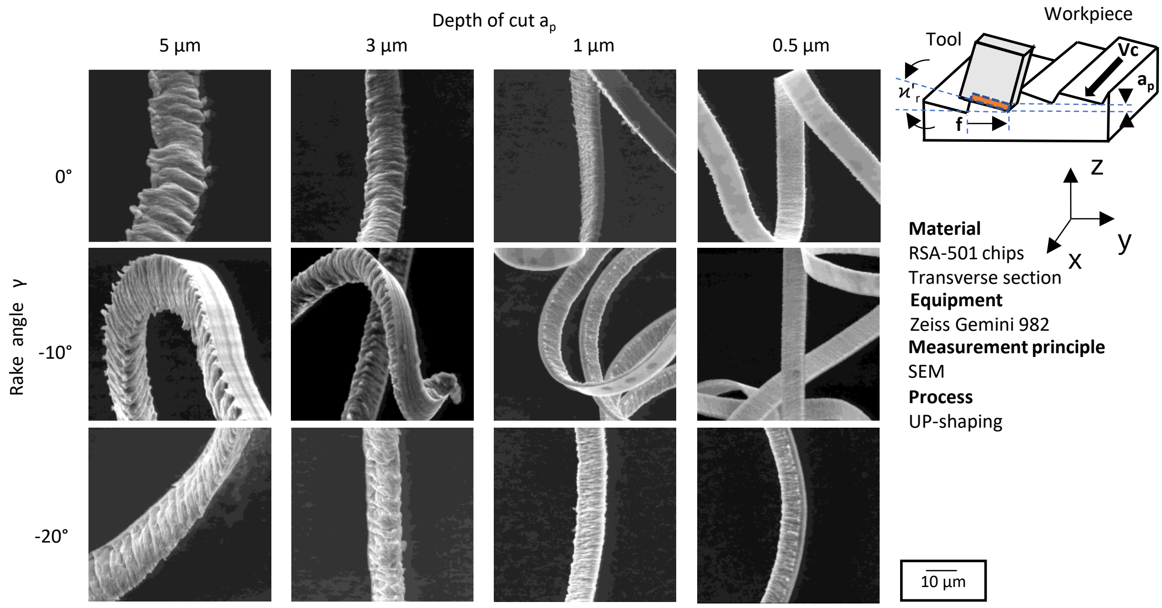

Figure 6 Chip samples of each parameter variation

to avoid collisions and unwanted effects of the material elastic recovery on the tool.

Images taken from the WLI were processed in the software Gwyddion. The percentage of surface defects was calculated based on the amount of black pixels (masks) observed on the surface of the blaze facet disregarding the blaze facets edges. The lines corresponding to the peaks and valleys of the grating structures were subtracted from the analysis. Figure 5 shows a matrix of processed images including the percentage of defects ρl. Understanding the chip formation and disposal during the UP-shaping of diffractive gratings is essential. One of the process characteristics is the continuous formation of chips along the cutting of a blaze facet. If the chip is not somehow removed or broken by the pressurized oil mist, it can substantially jeopardize the quality of the structure [8]. In this study, the produced chips from each process parameter variation were sampled using carbon tape and analysed by means of SEM. Figure 6 shows a matrix of the corresponding chips to the process parameter variation.

3.3. Surface characterisation of the machined grooves

Based on the results of the previous section, diffractive gratings were manufactured using the set of process parameters which incurs in less surface defects. Eventhough nanoindentation experiments did not indicate an anisotropy of the material, UP-shaping tests were conducted in two differently oriented segments of samples. One grating was manufactured in a cross-section of RSA-501. Another grating was manufactured in a longitudinal section, along the extrusion direction. Those gratings were measured using an AFM and the surface area roughness was measured on the blaze facets. Overall the average of 18 blaze facets were analysed and two exemplary surfaces of transversal section (TS) and longitunal section (LS) samples are presented in Figure 7.

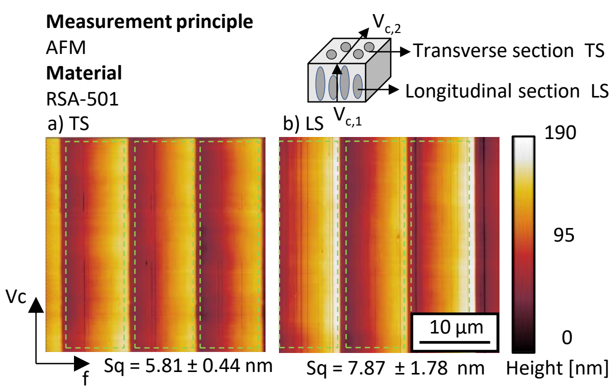

Figure 7 AFM measurements of exemplary blaze facets samples

4. Discussion

XRF and TEM-EDX measurements indicate that RSA-501 is not a homogenous material at the microscopic scale. The signals observed in the EDX measurements suggest the appearance of precipatations containing (Fe, Mn). Furthermore, despite Si being in small concentration, it is possible that the precipitate containing (Mg, Si) is also present within the alloy. Both precipations are harder than the matrix of polycrystalline Al and also brittle. The existance of $Al_3Sc_xZr_{1-x}$ precipitations was also reported by Bajaj [9]. However, it was not possible to detect them in the TEM measurements of this study due to too less magnification. These types of precipitants are limiting factors for a defect-free surface formation, since these elements have considerably different mechanical properties than the base material. Furthermore, the appearance of defects can be significantly increased by the cutting parameters and tool geometry.

By analysing the results of UP-shaping experiments, it becomes evident that two main factors contribute to the generation of defects on the blaze facet. By changing the rake angle towards negative values and keeping the depth of cut constant, the produced chips are lamellar. This chip formation favors the appearance of defects on the blaze facet. This is caused by a variation of the deformation during the cutting process, evidenced by the shear bands. The increase of defect appearance is due to the compression stress generated while cutting with negative rake angles γ. Therefore, the hypothesis is that harder precipitants are dragged over the surface of the blaze facets. Moreover, by employing negative rake angle, the chip flow is considerably hampered. Hence it is undesired while removing material. This can be compensated by a proper adjustment of the depth of cut a_p.

The second factor that favors the appearance of defects is the increased depth of cut a_p. Since the chip thickness, and therefore chip section also increases, it negatively influences the chip formation at the primary shear zone by diminishing the shear angle. Such cutting conditions also increase plastic deformation of the sample while cutting. This behaviour is proved by the lamellar chip formation. Since these precipitants are harder than the base material, they are broken, completly removed, or dragged during the UP-shaping process. Those factors are expected to influence the appearance of craters and groves on the blaze facets.

Nanoindentation experiments indicate no influence of anisotropic behaviour on RSA-501 hardness H nor E-module E. However, while analysing the results of UP-shaping process, indications of an improved Sq parameter is shown when cutting the TS surface of the sample. Nonetheless, the surface quality in LS as for TS seems to be strongly influenced by failures in form of grooves randomly appearing on the blaze facets. Since continous chip formation can also lead to the formation of a build-up edge in soft materials, the hypothesis is that these groove defects are a consequence of a build-up edge during the cutting process. For a better understanding of the defects found in RSA-501, more experiments and AFM measurements for the same and increased setting angle $\varkappa'r \geq 0.7°$ are necessary. Moreover, minor defects are expected to be a consequence of the precipitants (Mg, Si), (Fe, Mn) and (Al, Sc, Zr) that are dragged and/or completely removed from blaze facets.

5. Conclusion

Based on the obtained results it is possible to conclude that the process parameters during UP-shaping have a strong influence on the appearance of defects along the blaze facet. A proper setting of depth of cut a_p can significantly diminish their appearance on blaze facets. Such craters are probably related to the precipitations found in RSA-501. Since continuous chip formation favors build-up edges at the cutting tool edge, this phenomenon could be also strongly contributing to the generation of random deeper grooves on the blaze facets. Such defects influence the efficiency of diffractive gratings negatively by scattering the light depending on the applied wavelength. Moreover, there are indications of anisotropic behaviour during cutting of RSA-501. However, more tests for statistical representation are required. Overall, RSA-501 was proven to be a suitable material for manufacturing diffractive gratings, but further finishing processes could be of advantage.

6. Outlook

Since the efficiency of diffractive gratings depends on the blaze facet roughness among other properties, a defect-free and as smooth as possible blaze facet is required. For applications within shorter wavelengths, further investigations aiming at improving the surface roughness by means of finishing processes using ion beam etching are going to be investigated. For such processes, a complete understanding of the chemical composition and defects are essential. Therefore, to gain comprehensible understanding of the defect formation more experiments varying the setting angle $\varkappa'r \geq 0{,}7°$ and more blaze facets are required.

Acknowledgement

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