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Micro-endmilling of Fresnel structure on RSA 6061-T6 and PMMA

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Abstract

This paper aims to present both approaches of micro endmilling of stepwise-phase Fresnel lens in polymer and mold in non ferrous metal. The cutting was performed using a CNC machining Center. Optical profilometry and Scanning Electron Microscopy techniques were applied to assess surface finish, tool wear and chips formed after micromachining. The performance of the micromachining technique applied were compared for both materials in order to evaluate the choice and the viability of producing diffractive optical elements by micro end milling process directly in polymer or to fabricate a non ferrous metal mold for replications.

Micro endmill, ball nose, Fresnel sutructure, micromilling, surface integrity

1. Introduction

The advance in micromachining techniques has enable several approaches on different aspects of material removal in small scale [1]. The developments achieved helped in the improvement of machining conditions in order to obtain better surface integrity and tool performance [2]. There are different manufacturing processes that can be used to fabricate microstructures with optical functions such as Fresnel lens array [3-5]. The difference among them depends upon different aspects, to know: workpiece material, quantity, tolerances, costs, size, applications, etc.. Fresnel lenses are most commonly used in applications aimed at capturing light, for example in condenser systems or emitters / detectors. Fresnel lenses can also be used as magnifying and / or projection lenses [6]. Most commom processes used to fabricate Fresnel lenses are by direct micromachining of the Fresnel zones into polymer workpiece or by micromolding using a machined metallic mold [7]. The option of machining a Fresnel lens directly on a PMMA or on metal workpieces depends on factors such as: quantity demanded, application and functionality. Micro endmilling is generally used in the production of electronics, sensors, microheat exchangers, arrays of micro lenses as well as in molds and inserts [8]. When compared to chemical processes used in microfarbication, micro machining can be applied to the fabrication of three dimensional complex shapes. For instance, the machining of several Fresnel lenses off-axis generally demands a 3-axis machine tool and the endmilling process. The use of ball nose endmill tools can be considered a alternative choice to cut continuous-phase Fresnel lenses. However, in the case of machining stepwise-phase Fresnel lens the use of endmill cutter becomes the most suitable alternative. In this paper we will present both approaches of micro micromachining of stepwise-phase Fresnel lens in polymer sample and in non ferrous metal for molding using microendmill cutter. The cutting was performed using a CNC machining Center.

2. Methods and Materials

For the manufacture of PMMA lenses and aluminum molds in RSA 6061-T6 aluminum alloy, we used a CNC vertical machining center ROMI model D 600. The machine tool is equipped with the CNC Fanuc Oi - MD. We adapted an air spindle head with maximum spindle speed of 50000 rpm. The lenses and molds were machined from cylindrical samples of Aluminum RSA 6061 and PMMA (Figure 1 a), in which the RSA parts were fixed using an M3 screw, while the PMMA samples were fixed in the machining center, using a device, shown in Figure 1 b). We polished the both samples before cutting tests in order to have a mirror like surface finish. The root mean square (Rq) surface roughness for the aluminium alloy and the PMMA sample were, 8.96 nm and 7.47 nm, respectively.

The machinability of aluminum is high, due to its high ductiility, allowing its molding and machining in different formats. In addition, energy consumption during machining is low, with low environmental impact. Poly (methacrylate) or PMMA, also known as 'acrylic plastic', is a thermoplastic polymer widely used for optical applications, mainly due to the following properties: similarity to glass, good chemical resistance, high weather resistance, impact resistance, transparency and ability to reflect light. PMMA samples of 16 mm in diameter and 5 mm in height.

After defining the geometries of the lenses and molds, and the tools for micro-endmilling each one, the "Autodesk Inventor" software was used, in order to generate the 3D modeling of the parts through the CAD-CAM system, and obtain its machining simulation by setting the cutting parameters (Figure 2a). After simulating the parts (Figure 2b), the program generates the G code to be inserted in the CNC of the machining center. We used a LEO scanning electron microscope (SEM), model 440, operated under a power of 20kW, in order to assess the damage to the tools used, chip formation, and measure the condition of the micro-milled faces. The surface finish were measured using a WYKO NT1100 Optical profilometer.

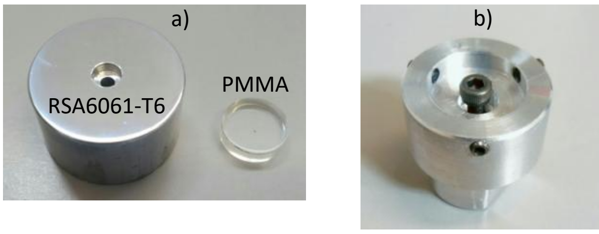


Figure 1. a) RSA60601-T6 and PMMA sample used in the cutting tests; b) Fixture for micro-milling of PMMA samples.

The stepwise-phase Fresnel lens machined are schematically represented in Figure 2. Figure 2 c) shows the convex shape of a aspherical Fresnel lens. Figure 2 d) and 2 e) show the stepwise-phase Fresnel lens shape

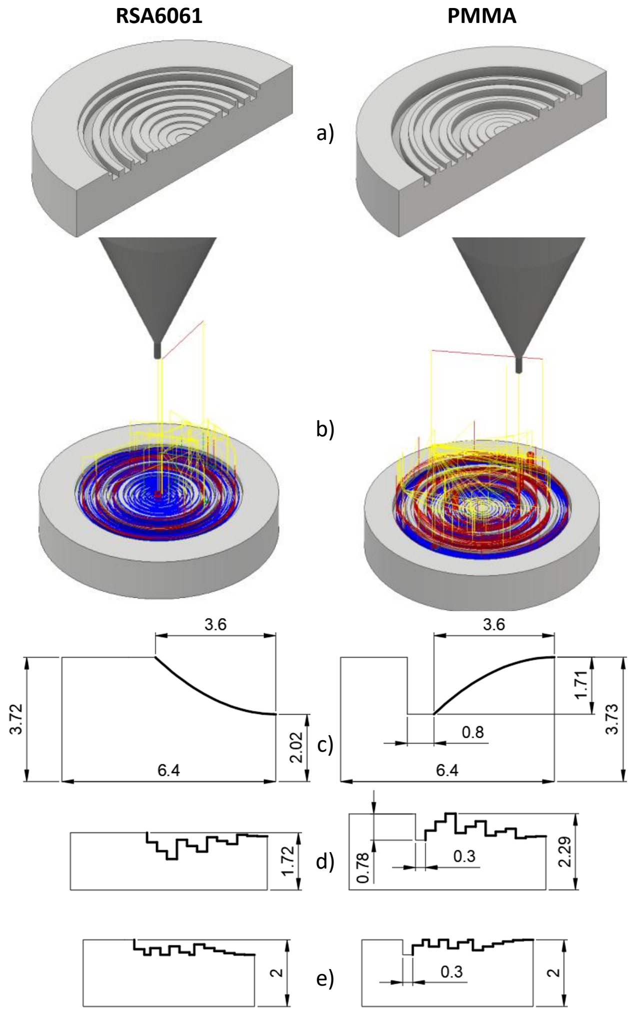


Figure 2. Schematic profile of the stepwise-phse Fresnel machined: RSA60601 and PMMA. A) 3D modeling , B) Simulating the parts, C) convex and concave shape, D) Variable height and E) Constant height

The endmill cutter used to machined the Fresnel profile in both materials is presented in Figure 3.

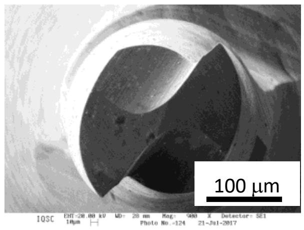


Figure 3. Scanning electron microscope image of the micro endmill cutter used to machine the stepwise-phase Fresnel in PMMA and RSA6061; top view, Endmill cutter diameter = 0.3 mm.

After machining, the microtopography of the surface was inspected by means of optical profilometer (Wyko NT 1100). The selected roughness parameter used to assess the surface finish was root mean square roughness (Rq) since information on optical performance of the machined surface is more representative.

The cutting strategy and cutting parameters used to machine the Fresnel profiles according to Fig. 2 are describe in Table 1. The tests, both in PMMA and RSA 6061, were performed under programmed feed of 500 mm / min, feed per tooth of 2.5 µm / rev, with a spindle speed of 50000 rpm. The machining tolerance used for the tool path generation and geometry triangulation configured in the program was 1 µm.

Table 1. Cutting strategy used in the rough and finish cut.

Work piece	R. Cut*	Max. ap [µm]	Max. ae [µm]	Stock mat. [µm]	F. Cut*	Max. ap [µm]	Max. ae µ[m]
RSA	P	30	240	10	P	15	220
RSA	P	30	240	10	P	150	220
PMMA	P	50	250	50	P	50	250
PMMA	P	50	300	20	p	20	300

*P:Pocket; R: Rough; F: Finish

3. Results and Discussion

Figure 4 show the three dimensional images and 2D analysis of the machined Stepwise-Phase Fresnel (variable height) shown in Fig. 2 **A** cut with microendmill cutter.

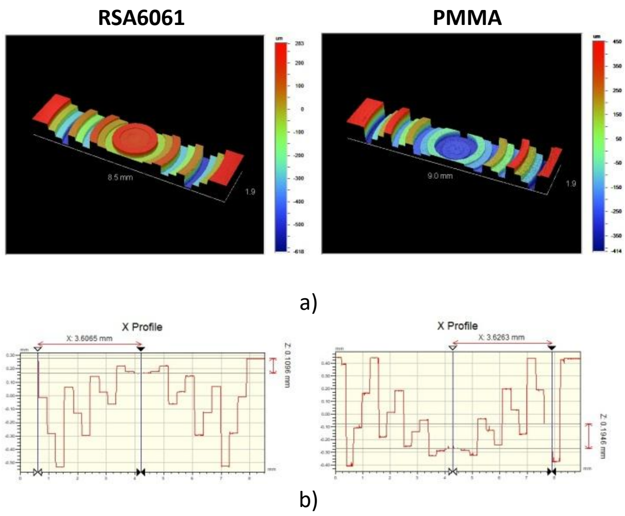


Figure 4. Images obtained by optical Profiler a) Three dimensional image of the machined Stepwise-phase Fresnel structures on different materials; and b) Cross-section profile of the machined samples with variable height.

Figure 5 show the three dimensional images and 2D analysis of the machined Stepwise-Phase Fresnel (constant height) shown in Fig. 2 **B** cut with microendmill cutter. We measure the root-mean-square surface roughness (Rq) of each zone from each sample and the average value from 3 measurements are shown in Table 2. The Rq values for the samples (metal mold and plastic lens) with variable height zones, shown in Fig. 4, presented close values among the the results, but the surface roughness for the PMMA sample presented slightly higher values in most zones. However, surface roughness results for the machined surface of the metal mold and the plastic sample with constant height zones Fresnel structure showed a more clear difference higher than 100 nm in some cases(*).

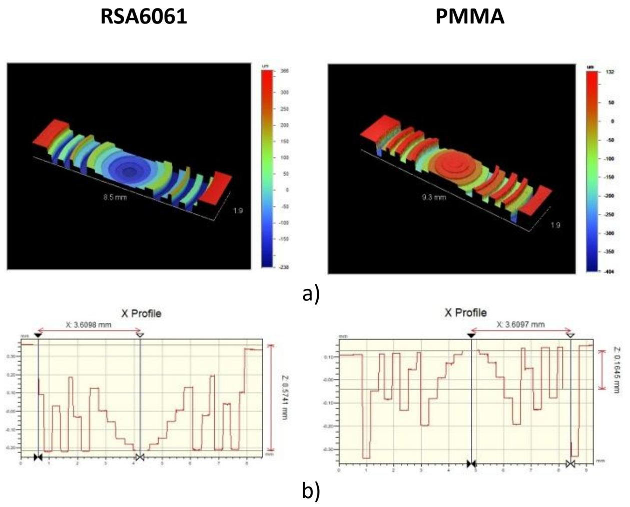


Figure 5. Images obtained by optical Profiler a) Three dimensional image of the machined Stepwise-phase Fresnel structures on different materials; and b) Cross-section profile of the machined samples with constant height.

Table 2. Average values of root-mean-square roughness (Rq) and standard deviation (σ) of each zone in the machined surface stepwise-phase Fresnel structures.

Zone	A 6061 Rq (nm)±σ	A PMMA Rq (nm) ±σ	B 6061 Rq (nm)±σ	B PMMA Rq (nm) ±σ
1	228,22±4.6	223,90±9.8	184,99±3.7	286,01±3.9
2	233,02±24.8	271,63±18	190,14±9.9	147,74±16.4
3	236,98±7.7	291,43±1.7	160,12±16.8	249,23±11.8
4	231,09±22.5	254,84±5.4	297,32±56.2	126,79±21.4
5	229,41±6.3	265,08±5.02	212,95±15.3	242,77±10.4
6	236,47±19.1	206,15±4.3	189,05±26.1	300,22*±24.02
7	231,71±14.7	273,85±9.4	205,71±16.4	131,28±1.63
8	275,44±19.4	229,88±11.9	192,10±39.8	229,34±29.5
9	243,77±15.4	229,88±11.9	222,23±19.1	255,60±22.1
10	221,70±0.8	194,88±29.2	186,46±8.1	265,95±12.4
11	181,68±8.1	222,70±19.7	181,68±17.9	246,35±39.4
12	189,64±24.85	216,60±19.6	166,59±29.8	251,75±12.62
13			155,31±2.3	128,54±5.6

Figure 6 show SEM images of the central zones of the constant height Fresnel metal mold and plastic lens. Fig. 6a shows the metal mold central zone where burrs are formed all around the board of the zone. The surface roughness in this case is greater than the plastic sample as it is presented in Table 2. Figure 6 b) shows the central zone of the plastic lens showing absence of burrs from cut of the prior zone.

Figure 7 zhow three dimensional images from the surface finish from the 9th zones of the variable and constant height Fresnel metal molds (Figs.7a and 7c) and plastic lens (Fig.7b and 7d), respectively. It is important noticing that, in both cases, the Peak-to-Valley values for the metal mold, machined under the same cutting conditions are smaller than the value from the plastic lens, despite the average values of root-mean-square roughness (Rq) be very similar for all samples within this zone, as shown in Table 2. Another aspect to be highlighted is the machined grooves marks left onto the surface by the cutting tool. This can be better observed in the images from the same zones probed by Scanning electron microscope shown in Figure 8. Figure 8 a) shows the cut grooves generated by the end-milling cutter on the RSA6061 surface. Figure 8b) shows shows the cut grooves generated by the end-milling cutter on the PMMA surface. The PMMA machined surface presents a *scale-like* surface generated during material removal. This surface texture may be attributed to the positive geometry of the tool, since the endmill cutter used has a small positive radial and axial rake angles. According to Carr and Feger [9], a positive rake will direct the force vector upward from the cutting plane, consequently, after the tool bit has passed, these little scales expand upward, increasing the overall roughness of the final surface. As the rake becomes increasingly positive, the magnitude of the excess increases.

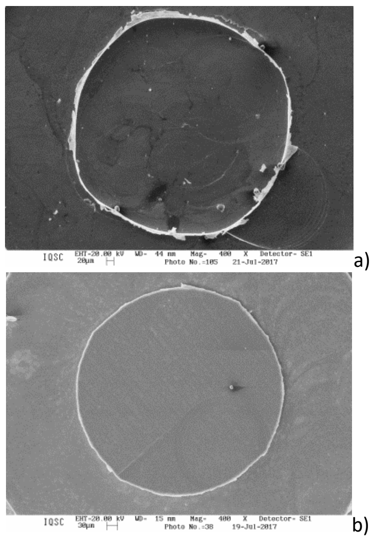


Figure 6. Scanning Electron Microscope images of the central zone of the Stepwise-Phase Fresnel structure with constant height, a) RSA6061-T6 metal mold and, b) PMMA lens.

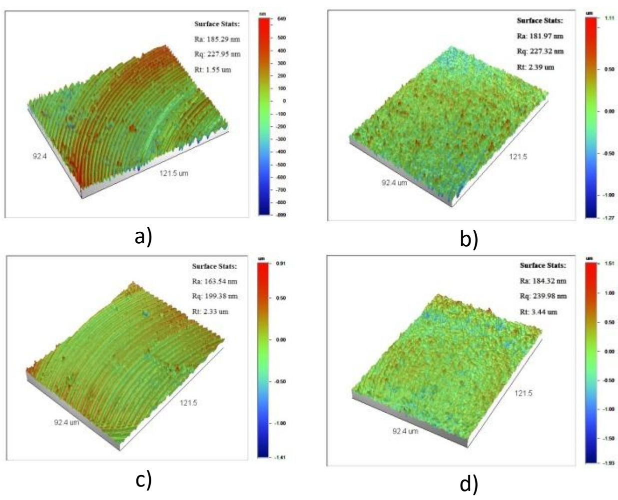
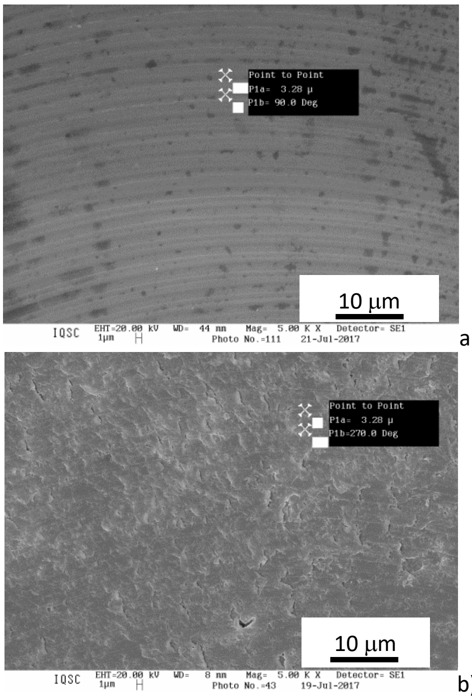


Figure 7. Three dimensional image made by optical profilometry from the machined surface in the 9th zone from al the samples: a) variable height Fresnel metal mold; b) variable

height Fresnel plastic lens; c) constant height Fresnel metal mold; d) constant height Fresnel plastic lens.



a)

b)

Figure 8. Scanning electron microscope images of the cut grooves generated by the end-milling cutter, a) RSA6061 surface b) PMMA surface.

4. Concluding Remarks

In this paper, we carried out the machining os Fresnel structures in a amorphous polymer and a fine grain aluminium alloy, to know: PMMA and RSA6061-T6, respectively. The stepwise-phase Fresnel lens structures were machined using a microendmill cutter with diameter of 0.3 mm. The Fresnel lens structure was machined directly on the amorphous polymer workpiece while the mold for this lens was machined in the RSA6061-T6 sample. The Peak-to-Valley values for the metal mold, machined under the same cutting conditions are smaller than the value from the plastic lens, despite the average values of root-mean-square roughness (Rq) be very similar for all samples within this zone. The machined grooves marks left onto the surface by the cutting tool observed in the images from the same zones probed by Scanning electron microscope show the that the PMMA machined surface presents a *scale-like* surface generated during material removal. This surface texture are attributed to the positive geometry of the tool, since the endmill cutter used has a small positive radial and axial rake angles. The surface roughness values are not low enough to be considered an optical finish. However it was possible to observed the main differences between the direct application of micro endmill cutter in polymer and non ferrous metals. Metals presented better results that can be attributed to its superior physical properties such as thermal conductivity and temperature of fusion as well as it mechanical properties. The possibility of direct machining is an important alternative since it allows to know the functionality of the lens structure. The use of a deterministic process such as micro endmilling instead of other available process used to fabricate such structure is also an advantage in terms of versality and rapidity to obtain free form structures. However, it is very important to note that these tests were carried out in a conventional machining center. The use of ultraprecision machine tools with greater rigidity and accuracy could offer much better results than those presented here. In addition, the use of tools with more precise and thin cutting edges, such as diamond tools, can also produce results closer to the requirements of these structures for application in optics and micro optics.

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