

Ultra-High Precision Machining of Modified High Strength Aluminium for Optical Mould Inserts

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Abstract

Traditional high strength aluminium grades such as AA6061 have been used in the high-precision industry to make components with excellent optical surface quality. AA6061 has become a successful material suitable for optics applications because of its relatively increased strength and excellent thermal stability. However, when used as a mould material for injection of plastic optics AA6061 imposes some difficulties when ultra-high precision machined with diamond tools. This includes the difficulty in producing ultra-fine finishes of the machined surface which is a critical quality of optical mould inserts. Recently, a modified grade of AA6061 has been used in optics applications. This grade (RSA 905) which is produced by rapid solidification demonstrates excellent optical characteristics. Surface finish of RSA 905 when diamond machined is noticeably finer than that of AA6061 thanks to the fine microstructure and precisely controlled composition of the material. This study investigates the quality of ultra-high precision machined optical convex surfaces having a big curvature radius. The effect of feed rate during diamond turning on the surface roughness of RSA 905 is discussed in this paper.

Keywords

Optical aluminium, Diamond turning, Mould inserts, Ultra-high precision machining

1 INTRODUCTION

Optical components made from plastic materials are found in various critical applications in different industries ranging from medical to aerospace. When an optical plastic element is produced in large numbers thermoplastic injection is the preferred technology employed because of its relatively short lead time. In plastic injection, forming cavities fabricated in mould inserts using ultra-high precision machining process (UHPM) are utilised. In the UHPM process cutting tools made from natural and synthetic diamonds are used to create high-precision optical surfaces on mould inserts made from high-strength non-ferrous materials such as aluminium and copper alloys of optical grades.

Recently, the optics industry has witnessed the development of new optical aluminium grades deliberately modified to address certain fabrication issues encountered when making optical mould inserts from those traditional optical aluminium grades currently available such as AA6061. Thanks to this development, today one can build a more durable optical mould insert when using these newly modified aluminium grades which are characterised by their specially tailored ultra-fine microstructure, increased strength and consistent mechanical properties. However, the literature unfortunately does not contain enough information on the performance of ultra-high precision diamond machining when manufacturing optical mould inserts

made from these recently modified optical aluminium grades.

Therefore, there is an urgent need to address this gap of knowledge on the production process of mould inserts from new optical aluminium grades. This can be achieved by conducting a series of machining experiments to comprehensively understand the behaviour of these new aluminium grades in terms of optical surface quality and the performance of the diamond machining technology used to manufacture mould inserts from these modified alloys.

The current study is dedicated to investigate the performance of the UHPM process when diamond turning an advanced grade of optical aluminium having an ultra-fine microstructure and subsequently an elevated ultimate strength. The paper reports on the effect of cutting conditions on the quality of the diamond machined optical convex surface shaped as mould inserts from advanced optical aluminium produced by rapid solidification.

2 ULTRA-HIGH PRECISION MACHINING OF OPTICAL ALUMINIUM GRADES

Optical aluminium grades such as Al6061-T6 are used for making optical mould inserts for plastic lens injection because of their high strength. However, they are not suitable for making glass moulds because of their relatively low tensile strength and

surface hardness compared to nickel-phosphorous (Ni-P) plated steels. Because of its low cost and small number of manufacturing steps required, aluminium could be a preferred choice when producing plastic injection mould inserts using UHPM.

Traditional aluminium grades for optical applications such as Al6061-T6 have been at the point of interest by many researchers. Liu et al. [1] used a slow servo tool to diamond-machine large aluminium optical components. They investigated the performance of UHPM and managed to achieve a surface roughness of 10 nm. Revel et al. [2] conducted experiments of diamond turning of a number of optical aluminium alloys including a pure aluminium grade. They examined the machined surface characteristics and found that the least roughness was obtained when diamond machining pure aluminium. The other aluminium alloys produced high roughness due to the presence of precipitates. The change in the material microstructure at the machined surface and subsurface layers as a result of the localised heating occurring in diamond machining of Al6061 was studied by Wang et al. [3]. They concluded that the machining temperature at the tool-workpiece contact zone can reach 500°C, which is a high temperature for aluminium.

The studies mentioned above have been focused only on diamond machining of conventional aluminium alloys. The industry has recently witnessed the development of special and modified aluminium grades characterised by their increased ultimate strength. This is thanks to the recently developed advanced foundry and melting technologies. Nowadays, the melt-spinning technology with rapid solidification rates can be employed to produce rapidly solidified grades of aluminium super alloys for optical mould making. Such alloys have fine nano-structures that result in highly improved mechanical and physical properties [4-9].

Rapidly solidified aluminium (RSAL) grades have demonstrated their outstanding performance when used as a mould material for plastic optics injection. Gubbels et al. [10] investigated the performance of mould inserts made from RSAL and other two mould materials (beryllium copper and 6061 aluminium). They found that machining of RSAL resulted in finer surface finish of the mould inserts compared to the other two materials. This was accounted for the fine microstructure of the RSAL which resulted in finer cutting streaks on the machined surface of the insert. In another study, To et al. [11] conducted diamond-turning experiments on rapidly solidified Al6061 (called RSA 6061) with diamond inserts of 0° rake surface angle. They concluded that diamond machining of RSA 6061 resulted in very small roughness values (2-3 nm) in shorter machining steps. This roughness was less than that of other traditional mould material such as nickel-

phosphorous plated steel which required more processing steps to obtain small values of roughness.

From the literature review discussed above, it can be concluded that ultra-high precision machining of the modified optical aluminium grades has been given only little attention by few researchers unlike traditional optical aluminium such as Al6061. Therefore, there is an increasing need to look at high precision diamond machining and machined surface quality resulting from turning those recently developed aluminium grades which have been modified by rapid solidification process during spinning melting.

The current paper contributes to the area of optical mould making by looking at the machined surface integrity received after UHPM of new optical aluminium grades developed by melt-spinning with rapid solidification.

3 EXPERIMENTAL PROCEDURES

This experimental study is focused on investigating the effect of machining parameter and feed rate in particular on the machined surface quality when turning an advanced grade of optical aluminium on an ultra-high precision machining centre using diamond tools.

3.1 Rapidly solidified optical aluminium

The aluminium workpiece machined in this study was produced by melt-spinning process at a cooling rate of 10⁶ C°/s. The high solidification rate resulted in an ultra-fine microstructure of the material. Therefore, the material exhibits excellent mechanical and physical properties compared to other optical aluminium grades produced by traditional foundry.

RSA 905 rapidly solidified aluminium workpieces of 18-mm diameter and 40-mm thickness were developed by RSP Technology Ltd (the Netherlands). The workpieces were diamond turned to shape convex mould inserts of 100-mm convexity radius.

The typical chemical composition of RSA 905 is shown in Table 1. The iron related particles are present in a large amount. These particles are highly brittle and usually possess sharp edges. Therefore, when diamond machined, these iron compounds will break under the combined shear and compression effect [11]. This might cause rupturing during machining and affect the machined surface finish. However, rapid solidification results in small sizes of these particles and thus a less harmful effect than that of traditional optical aluminium will occur on the machined surface.

Element	Fe	Ni	Cu	Mn	Mo	Zr
Wt%	2.5	5	2.5	1	0.8	0.8

Table 1 - Typical composition of RSA 905

3.2 Ultra-high precision machining setup

The diamond machining tests were conducted on an ultra-high precision machining centre (Nanoform 250 Ultragrind) that has the ability to provide axis motion at a resolution of 0.1 nanometres. The machining setup employed for diamond turning of RSA 905 is shown in Figure 1. Two axes (X and Z) out of four were manipulated to shape a convex surface on the RSA 905 aluminium workpieces.

In this study we used standard non-controlled waviness mono-crystalline natural diamond inserts mounted on a horizontal 0°-tool holder to machine the RSA 905 samples. The diamond inserts had a negative back rake angle of -25° and clearance angle of 5°. The inserts were manufactured by Contour Fine Tooling Ltd (UK) with a nose radius lapped to 1.5 mm.

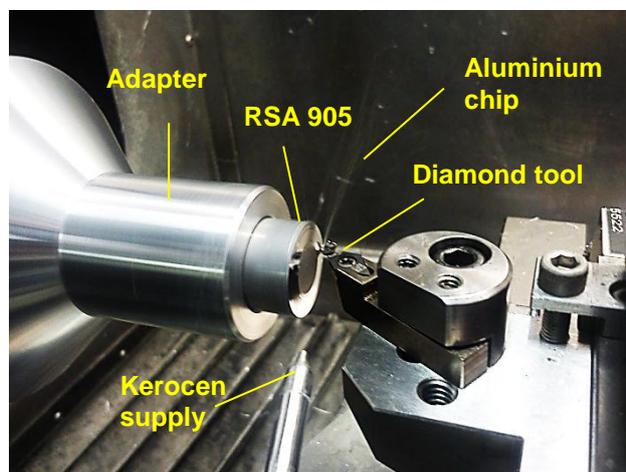


Figure 1 - Diamond machining setup of RSA 905

Workpiece	Rapidly solidified aluminium (RSA 905)
Tool	Single crystal natural diamond
Rake angle	-25°
Relief angle	5°
Nose radius	1.5 mm
Spindle speed	2000 rpm
Depth of cut	25 µm
Feed rate	2.5, 7.5 and 12.5 µm/rev

Table 2- Diamond machining parameters of RSA 905 rapidly solidified aluminium

Diamond turning of RSA 905 was performed in the presence of odourless kerosene mist used as a coolant. The machining tests were performed at constant cutting parameters except for the feed rate. The depth of cut and cutting speed were kept unchanged at 25 µm and 2000 rpm, respectively. Three diamond inserts were used for three different feed rates: 2.5, 7.5, and 12.5 µm/rev. Therefore, in this study in addition to evaluating the machinability of RSA 905 when diamond turned, the effect of varying the feed rate was also addressed. The

cutting conditions of the diamond machining experiments are summarised in Table 2. Before conducting the final turning finish test, the workpiece was rough machined with another negative-rake synthetic diamond insert and a mirror surface of ultra-fine roughness was prepared for the experimentation.

4 RESULTS AND DISCUSSIONS

The present work is focused on investigating the performance of UHPM when diamond turning recently developed rapidly solidified aluminium. The effect of machining parameters, and in particular the effect of feed rate, are studied. Figure 2 shows the aluminium convex surface produced by diamond turning. The machined surface has been examined for its roughness after 3.5-km cutting length using an atomic force microscopy (AFM).



Figure 2 - Diamond machined convex lens from RSA 905 aluminium

The statistically processed surface roughness values received from the AFM for the three feed rates are indicated in Figure 3. Although the machining tests were conducted at a relatively large depth of cut (25 µm), one can generally conclude that the selected cutting parameters yielded excellent surface finish of high optical quality (2-3 nm). This finding is in agreement with that concluded in the study conducted by To et al. [11]. However, To et al. [11] used a finer depth of cut (10 µm). This means that the selected combination of cutting parameters and tool geometry employed in this study managed to yield a high material removal rate at an excellent optical surface finish

The lowest surface roughness indicator (R_a) was obtained at the highest feed rate ($R_a = 2.7$ nanometre) while at the lowest feed rate (2.5 µm /rev) the roughness was slightly bigger ($R_a = 3.7$ nanometre). However, the surface roughness at the middle feed rate (7.5 µm /rev) was about 17 nanometre. This could be explained by the kind of chips removed at this feed. In this case, unlike the other two feed rates (lowest and highest), the chips

tended to curl and tangle around the tool tip rather than moving away from the cutting zone.

Figure 4 shows a snapshot of the tool and workpiece after few cutting passes conducted at the 7.5- $\mu\text{m}/\text{rev}$ feed rate. From the Figure, it is evidenced that the chip was not of the desired type. The chips did not slide away, as in the other two experiments (see Figure 1), and just tangled around the tool and workpiece in the cutting zone. This phenomenon causes rubbing action of the chips against the already machined surface and thus leads to severe deterioration of the surface optical finish.

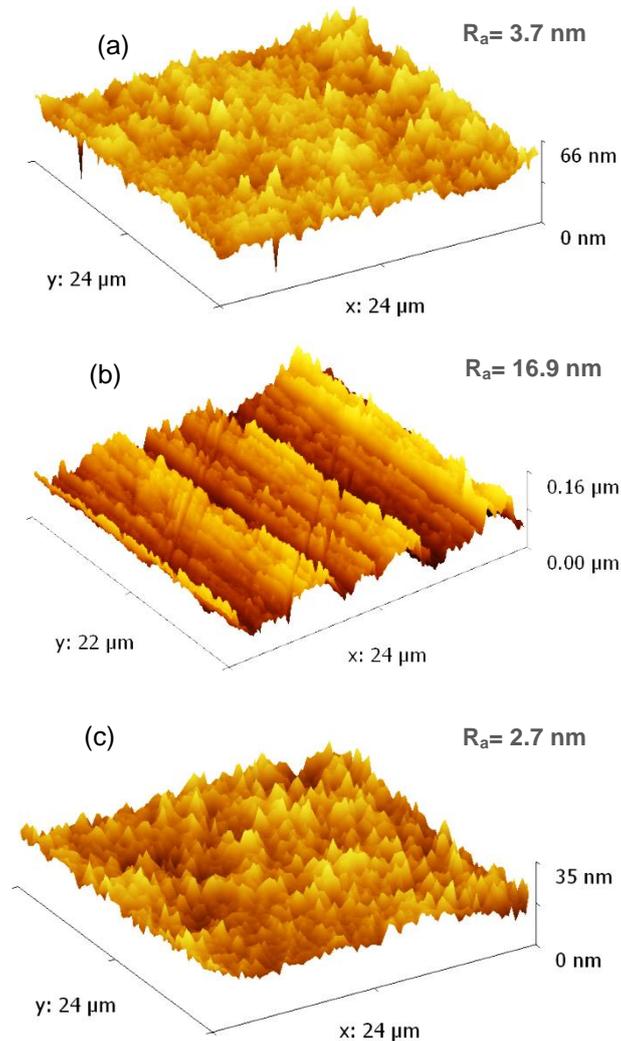


Figure 3 - Surface AFM topographic images at feeds: (a) 2.5, (b) 7.5 and (c) 12.5 $\mu\text{m}/\text{rev}$

5 CONCLUSIONS

Rapidly solidified aluminium has been developed to replace traditional optical aluminium grades in making mould inserts for plastic injection of optical elements. Therefore, there is a need to look at the aspects of ultra-precision diamond turning of RSA. This paper is concerned with investigating the performance of ultra-high precision machining when

diamond turning RSA 905 meant for making optical mould inserts. The paper aims in particular at finding the effect of feed rate on the machined surface quality.

Although the machining tests were conducted at a relatively large depth of cut (25 μm), one can generally conclude that the selected cutting parameters yielded surface finish of optical quality. For the lowest and highest feed rates, the surface finish is in the range of 2 to 3 nanometres. However, if the chip removal mechanism forces the chip to curl and tangle around the tool tip as in the case of the 7.5- μm feed, the machined surface gets affected by the rubbing action of the micro-chips and this will cause the surface to rapidly deteriorate.

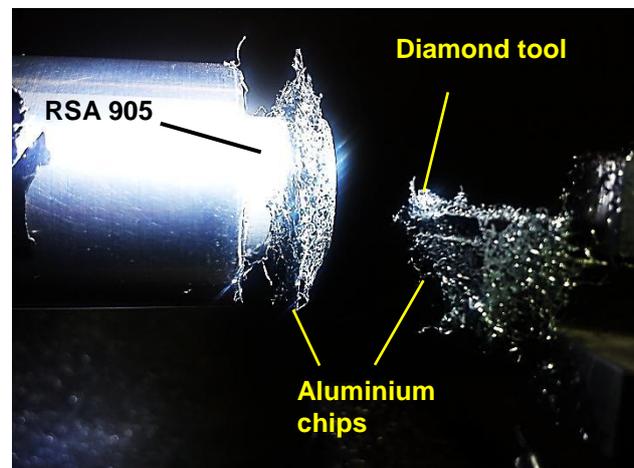


Figure 4 - Behaviour of chip removal at middle feed rate (7.5 μm)

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