AE MONITORING OF DIAMOND TURNED RAPIDLY SOLDIFIED ALUMINIUM 443

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Abstract. The fast replacement of conventional aluminium with rapidly solidified aluminium alloys has become a noticeable trend in the current manufacturing industries involved in the production of optics and optical molding inserts. This is as a result of the improved performance and durability of rapidly solidified aluminium alloys when compared to conventional aluminium. Melt spinning process is vital for manufacturing rapidly solidified aluminium alloys like RSA 905, RSA 6061 and RSA 443 which are common in the industries today. RSA 443 is a newly developed alloy with few research findings and huge research potential. There is no available literature focused on monitoring the machining of RSA 443 alloys. In this research, Acoustic Emission sensing technique was applied to monitor the single point diamond turning of RSA 443 on an ultrahigh precision lathe machine. The machining process was carried out after careful selection of feed, speed and depths of cut. The monitoring process was achieved with a high sampling data acquisition system using different tools while concurrent measurement of the surface roughness and tool wear were initiated after covering a total feed distance of 13km. An increasing trend of raw AE spikes and peak to peak signal were observed with an increase in the surface roughness and tool wear values. Hence, acoustic emission sensing technique proves to be an effective monitoring method for the machining of RSA 443 alloy.

Keywords: Rapidly Solidified Aluminium (RSA), Melt spinning process, Ultra-High Precision Diamond Turning (UHPDT), Acoustic Emission(AE), Root Mean Square (RMS), Single Point Diamond Turning (SPDT), Total Integrated Scatter (TIS).

1. Introduction

Previously, diamond turned and more recently polished conventional aluminium AA6061 had been widely employed in the production of mirrors used for astronomical and terrestrial instruments. Reasons are understandably from its reflective properties, high specific stiffness
and the ability maintain the coefficient of thermal expansion when subjected to severe temperature conditions [1, 2]. Furthermore, a low cost is incurred while applying AA6061 to astronomy due to sufficient available data on this material, hence selecting the material does not require new certification trajectories [1].

However, conventional AA6061 is a polycrystalline material which comprises of different crystallographic orientations creating differences in hardness and shear incompatibility in the neighbouring grains. This inherent defect creates a major drawback as the single point diamond turning of AA6061 can only produce surface roughness values in the range of 5-8nm which is only adequate for the infrared spectral range but not for the visual spectral range and near ultraviolet (NUV) spectral range [3]. Alloys with smaller grain size can produce better surface roughness values which determines the Total Integrated Scatter (TIS) [4].

Total integrated scatter from a given mirror surface is determined by the ratio of the frequency band-limited root mean square surface roughness (Rq) to the wavelength of light (λ) and it us used to measure the amount of scatter from the total reflected light by a given mirror [5]. The TIS equation (Eq. 1) below infers that the minimum surface roughness (Rq) required to generate 1% scatter at a minimum visual wavelength (λ) of 300nm will be 2.38nm which is about half the achievable surface roughness value of conventional aluminium alloy [4]. Different methods have been successful applied to achieve lower surface roughness values while machining AA6061, though not without some inherent challenges. One of these methods is plating with high purity aluminium before machining. The Alumni plating is known to have achieved a surface roughness of 2-4nm but it creates a difficulty in cleaning the machines surface due to its softness [1]. The use of nickel plating before machining also helps to achieve a surface roughness range of 1-2nm but the difference in the thermal expansion of nickel and aluminium could result in bimetallic bending at extreme temperatures [1]. Furthermore, extra cost and time is incurred with the process of plating conventional aluminium or optical polishing to achieve better surface roughness values. These conditions are not desirable in a manufacturing process.

\[
TIS = \left[ \frac{4\pi Rq}{\lambda} \right]^2 \quad Rq << \lambda
\]  

(1)

From a comprehensive view, the developing trends in the use of aluminium for optical applications are viewed from two broad categories. Firstly, an improvement on the material structure observed progressively from the use of traditional aluminium to conventional aluminium 6061 and the birth of rapid solidification processes for the development of rapidly solidified aluminium grades like 905,708, and 443. Secondly, a development of the machining processes employed for the production of the optics in relation to improving on the required shapes and accuracies. As a result, instigating a rise in the need for effective process monitoring techniques. This process monitoring strategies help to study and understand the performance of the newly developed RSA alloy grades and their manufacturing processes.

With these recent development of interested researchers in RSA alloys 901, t6, 708, etcetera. There is limited available literature on AE monitoring of diamond turned RSA alloy 443.
2. Literature Survey
2.1. Rapidly Solidified Aluminium
Conventional aluminium materials are produced through powder metallurgy which cannot achieve the best uniformity of the alloying elements [2, 6]. Rapid solidification can be used to achieve the following: formation of new metastable phases, extension of the solid solubility to give precipitate strengthening and solute strengthening and refinement of the grain size of the matrix and other constituents to give fine grain strengthening [7-9]. Rapid solidification processes are now being applied to overcome the inherent challenges with conventional aluminium through refining the structure of the aluminium alloys. This process helps to manufacture uniform aluminium alloys with small grain sizes hence reducing the use of exorbitant and vulnerable plating to achieve lower surface roughness values [1]. Furthermore, rapidly solidified aluminium alloys contain fewer impurities which is advantageous as it reduces the chances of break outs occurring during subsequent polishing [2].

The fundamental principle in rapid solidification process is the removal of heat from a mass of liquid metal at a fast rate. Generally, this is made possible by controlling a thin mass of liquid metal in a particular dimension to be in good thermal contact with an efficient heat sink [10]. A range of diverse rapid solidification processes have been developed including: inert gas and water atomisation [11, 12], laser and electron beam surface melting [13], melt extraction [11], melt spinning and planar flow casting and plasma and atomised spray deposition [11]. Judging from the grades produced, melt spinning is the best rapid solidification technique [7].

The melt spinning process is a rapid solidification technique with cooling rates up to $10^6$ k/s. The melt is prepared using different alloying elements which is poured through a small nozzle on a rotating copper wheel to obtain rapidly solidified ribbons. The ribbon is chopped to flakes and gathered in a vessel at high cooling rates in the range of 1Mk/s. The flakes are degassed and subjected to hot isostatic pressure at which a consolidated material can be realized in the form of billets [2]. These billets can be further extruded or forged to required dimensions. The process provides the ultimate solution for light weight high-end applications in optics, precision equipment, aerospace, medical, electronics and automotive industries [6]. Melt spinning process (MSP) has proven to be a better manufacturing method compared to powder metallurgy since it can be used to refine the grain size of the aluminum about 10-50 times thereby making the grain size of rapidly solidified aluminum alloys very small compared to the conventional aluminum. As a result, RSA alloys can be machined to smaller surface roughness values for applications in the near ultraviolet wavelength spectral range because MSP generates ultrafine and homogenous micro structures which enable better diamond turning and surface finish generation hence more suitability for a wide range of optical applications.

2.2. UHPDT of Rapidly Solidified Aluminium Alloys
With the advancement in technology and increase in material application to the development of micro-parts, moulding process has become an indispensable mass manufacturing process. Therefore, several products, micro-lenses and micro-components are being manufactured by moulding process. Furthermore, the molding process has been widely employed in plastic and glass lens production, automobile, aerospace and other manufacturing industries [14].

6061 Aluminum alloys, nickel coated steel alloys and beryllium copper alloys have been frequently used in the production of lens mold inserts because they are easily processed with single point diamond turning [15]. Of these materials, Al 6061-T6 was a preferred choice for mold inserts due to its high machinability, and low density owing to ease of assembly unlike
steel which cannot be easily cut because it inflicts serious wear on the single point diamond tool and beryllium copper which require relatively costly machining tools due to its high strength\cite{15,16}. However, the strength and low wear resistance limitations of aluminium alloys poses a major disadvantage in molding inserts \cite{16}.

The quality of mold inserts is determined by the surface finish of the mold insert. Zhong and Gubbels et al concluded that ultra-precision machined RSA grades generated better surface finishes when compared with other moulding materials \cite{1,14}. Furthermore, To et al achieved a surface roughness of 2-3nm in fewer machining steps and less tool damage with RSA 6061 on the other hand, nickel plated steel generated a higher margin of surface roughness values with the same number of machining steps \cite{17}.

Furthermore, tool wear investigation on ultra-high precision diamond turning RSA 905 alloy by Abou-el-hossein et al has revealed that minimum abrasion occurred at low feed but achieved a highest value at the middle range of feed for the selected levels of machining parameters \cite{18}. A recent study on diamond insert wear while turning RSA 443 alloy revealed that reduced cutting speed degenerated to increased tool wear and higher surface roughness occurred at lower spindle speed while feed rate effect was not as significant as the spindle speed. However, the flattened tool edge which occurred as a result of increased time and machining distance improved on the surface roughness. It was also suggested that surface roughness of RSA443 alloy will increase with the further advancement of tool wear \cite{19}.

### 2.3. AE Sensing Technique

Acoustic emission waves are low amplitude energy waves with a high frequency up to 50MHz, occurring as a physical phenomenon propagating through a structural lattice dislocation and atomic level disturbances \cite{20}. Over the years this phenomenon has been proven to be invaluable in the monitoring manufacturing processes and machining conditions. Compared to other prevalent monitoring techniques applying force, vibration, pressure and temperature sensors, AE monitoring has achieved a high success rate due to its high signal to noise ratio and sensitivity even at micro scale cutting depth where other monitoring techniques are not efficient \cite{21}. Furthermore, its immunity to low frequency noise source and environmental noise influence is a desirable consideration for monitoring techniques.

AE monitoring has been applied to monitoring several macro and micro machining operations ranging from turning and milling to the different modes of grinding but there is no available literature on AE monitoring of RSA 443 alloy grade. Abou-el-hossein et al investigated the tool wear encountered during ultra-high precision machining of RSA 905 alloy using acoustic emission sensing technique. They observed a notable change in AE raw and rms features for different conditions of tool wear and surface roughness. Furthermore, they observed higher amplitudes of raw and rms AE signals occurring at 25mm/min feed rates compared to 15mm/min feed category although the tool wear at 25mm/min was less than 15mm/min \cite{22}.

### 3. Experimental Design

#### 3.1. Workpiece

RSA 443 alloy has fine microstructure and is relatively harder than traditional aluminium because of its high silicon content. The research was carried out on RSA 443 grade with 60.5 mm diameter, manufactured by RSP technology Ltd. This workpiece contains about 40% silicon, having a low thermal expansion, density, high specific thickness and high thermal conductivity. Table 1 highlights some physical and mechanical properties of RSA 443.
Table 1. Mechanical properties of RSA 443 Alloy

| Property            | Value |
|---------------------|-------|
| Composition         | Al, Si0.4 |
| Hardness            | 105   |
| Density [g/cm³]     | 2.54  |
| Thermal expansion [10/k] | 13.6  |
| Young’s modulus [GPa] | 102   |
| Ultimate tensile strength [MPa] | 245   |
| Yield strength [MPa] | 155   |
| Elongation [%]      | 1.5   |

3.2. Parameter Selection

Three machining parameters: feed rate, cutting speed and depth of cut were varied for the experimental study. These parameters were varied at three levels as shown in (Table 2).

Table 2. Machining parameters and combination

| Parameter   | Combination |
|-------------|-------------|
| Feed [mm/min] | 5  15  25 |
| Depth [µm]   | 5  15  25 |
| Speed [rpm]  | 500 1750 3000 |

3.3. Machining setup

A 4 axes ultra-high precision lathe machine (Nanoform 250), manufactured by Precitech was utilised for the research (Fig. 1). The machine boasts of 0.1 nm control resolution. Diamond tool inserts by Contour Fine Tool Ltd were used in the research with a nose radius 0.5mm, rake angle -5° (mounted on a 0° tool holder) and front clearance 10° (mounted on a 0° tool holder) and standard waviness. The tool was centred using a visual display unit coupled to an integral Precitech while the coordinates of the radius and flank radius were recorded. (Fig. 2).

With help of an adaptor the workpiece was fastened and mounted on the machine’s vacuum chuck while the specimen was centered according to its perimeter using an electronic dial test indicator. At 2000rpm, the chuck was rotated together with the specimen to ensure balance while kerosene coolant was used to prevent thermal damage to the work piece.

Surface roughness measurements on the workpiece were carried out using Taylor Hobson PGI Dimension XL Surface Profilometer which is a 3D nano-profiler that has 0.2 nanometre resolution (Fig. 2). Surface roughness measurements carried at different intervals. Using a sampling length of ± 4 mm, three consecutive measurements were taken on the machined surfaces and the average was calculated and recorded. The tool insert wear was measured using a JOEL JSM- 6380 Scanning Electron Microscope (SEM) as the inserts were mounted on a special stub holder for positioning in the SEM chamber. In order to measure the length and width of the wear area, The X-Y and R controls axis of the SEM were manipulated to bring the required insert face (edge) to view.
3.4 Acoustic emission set up.

Acoustic emission data was acquired at a high sampling rate of 2million samples per second using a Kistler piezo-electric sensor. The AE sensor was attached using a magnetic clamp. The AE sensor connection comes with a built in coupler unit for signal pre-processing. Signal filtering was done with a band pass filter range (5 KHz – 700 KHz) and a gain amplification of 20db. The AE signals were further relayed to National Instrument (NI) BNC board and a 16bit NI PIC 6110 data acquisition card for further processing. AE data acquisition code for real time acquisition was developed with the use of a Graphical User Interphase (GUI), NI Virtual Instrumentation Engineering Workbench (LabVIEW).
4. Results and Discussion
The results recorded below and the corresponding AE data from some of the experimental combinations were measured and acquired after the feed has travelled a machining distance of precisely 13km (Table 3). Only raw AE signal voltages were acquired during the course of the study. The tool numbers are classified as LH (left hand) and RH (right hand).

Table 3. Surface roughness and wear measurement results

| Tool no | Cutting speed [rpm] | Feed [mm/min] | Depth [µm] | Ra[20] | Wear[20] |
|---------|---------------------|---------------|------------|--------|-----------|
| 72LH    | 1750                | 25            | 25         | 37     | 8         |
| 72RH    | 500                 | 5             | 15         | 24     | 6.5       |
| 73RH    | 1750                | 5             | 5          | 14     | 3         |
| 74LH    | 3000                | 5             | 15         | 13.5   | 2         |
| 74RH    | 500                 | 15            | 5          | 43     | 8         |
| 75LH    | 1750                | 15            | 15         | 21     | 4         |
| 77LH    | 500                 | 15            | 25         | 50     | 15        |
| 78LH    | 3000                | 25            | 15         | 28     | 7         |

The AE signals were subjected to band pass filtering and segmented to an online time segment window approximately 5 seconds. The average amplitude of the raw AE signals in all the different combinations were observed to vary between 0.02Volts and 0.05Volts for the different parameter, surface roughness and wear conditions (Fig. 4 – Fig. 9).
Figure 4. 77LH, Ra 50nm, Wear 15nm

Figure 5. 74RH, Ra 43nm, Wear 8nm

Figure 6. 78LH, Ra 28nm, Wear 7nm
Figure 7. 72RH, Ra 24nm, Wear 6.5nm

Figure 8. 75LH, Ra 21nm, Wear 4nm

Figure 9. 74LH, Ra 13.5nm, Wear 2nm
Moreover, a noticeable trend was observed with some raw AE time series features which are maximum value and peak to peak value of the AE waves. The peak value of the dominant spikes and the peak to peak values in the raw AE signals indicate an increase with the surface roughness and wear. A summary of the trends for maximum AE amplitude (AE\text{MAX}), minimum amplitude (AE\text{MIN}) and peak to peak values are represented in (Table 4 and Fig. 10).

| Tool No. | Ra[20]| Wear[20] | AE\text{MAX} x 10^{-2}[V] | AE\text{MIN} x 10^{-2}[V] | AE_{P-P} 10^{-2}[V] |
|----------|-------|----------|--------------------------|--------------------------|---------------------|
| 77LH     | 50    | 15       | 0.080                    | -0.073                   | 0.153               |
| 74RH     | 43    | 8        | 0.068                    | -0.075                   | 0.143               |
| 78LH     | 28    | 7        | 0.074                    | -0.074                   | 0.1                 |
| 72RH     | 24    | 6.5      | 0.060                    | -0.061                   | 0.121               |
| 75LH     | 21    | 4        | 0.049                    | -0.050                   | 0.099               |
| 74LH     | 13.5  | 2        | 0.039                    | -0.004                   | 0.079               |

From table 4, maximum value of the AE signal (8.0 x 10^{-2}V) and peak to peak (15.3 x 10^{-2}V) were observed at 50nm surface roughness with a corresponding wear of 15nm. On the other hand, a minimum value of AE raw signal (4.0 x 10^{-2}V) and peak to peak (7.9 x 10^{-2}V) were observed to correspond with low values of 13.5nm surface roughness and 2nm wear (Fig. 10).

![Figure 10. Increasing trend of AE features and wear with surface roughness](image)

An exceptional case was observed at surface roughness of 28nm and wear of 7nm with AE maximum spike clearly higher than the immediate neighbouring points on the chat (Fig 10). This could be because of the high levels of machniing parameters (3000[rpm], 25[mm/min])
and 15[µm]) used for this particular run. AE spikes are normally higher with an increased speed, feed and depth of cut.

Furthermore, previous studies show that surface roughness values increase with lower values of the cutting speed as also observed by Aboul el hossien et al. Within the range of their experimental design parameters, they also observed time series AE rms levels to be highest at a feed 15mm/min for RSA905 alloy [22] in contrast to the maximum AE spike and peak to peak observed for RSA443 alloy at 25mm/min feed rate. However, the average raw AE levels were closer to the 0.05[V] mark at a feed of 15mm/min for RSA 443 with which corresponds to high value of surface roughness and wear condition.

Abou-El-Hossein et al also noted the improved surface roughness conditions with the increase in machining time as the tool wear flattened out after the initial stage of wear and predicted a possible increase in surface roughness values as the tool wear further deteriorates [18]. Hence, from our observation so far, it is safe to posit that an increase in AE spikes which corresponds to increased surface roughness values could occur with further significant increase in machining distance covered for RSA 443 alloy.

5. Conclusion

Despite the high silicon content present in RSA443 similar AE signal behaviours were observed to be maximum at 15mm/min while more influence of the cutting speed could be noticed overall on the surface roughness, wear and AE signal spike levels. The Raw AE signals spikes and peak to peak values were observed to increase with an increase in surface roughness and tool wear respectively. Therefore, acoustic emission sensing with Raw AE signal monitoring has proved to be an efficient means of monitoring diamond turning RSA443 for optical mould inserts.

The monitoring technique can be further improved by extracting relevant direct features from the raw AE signals which could better relate directly to condition of the tool and surface roughness. Furthermore, the potential noticed with the AE sensing technique should be able to solve the dilemma of determining the transition point from initial wear stage to flattened tools and further extreme wear conditions in diamond turning of RSA443 alloys. Further analysis will be done on the raw AE signals to ascertain the frequency characteristics in relation to the surface roughness and wear.

6. References

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