Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS2) nanolubrication in end milling machining

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Abstract

Aluminum alloys are among the most significant metals in industries. The AL6061-T6 aluminum alloy is a highly prominent alloy due to its dominant mechanical properties, such as weldability, hardness and sustainability at high temperatures. AL6061-T6 is commonly used in heavy industries including aerospace, aircraft, automotive, food packaging, etc. Milling of AL6061-T6 is important, especially to create product shape varieties for different applications. However, the demand for high quality draws attention to product quality, particularly machined surface roughness, as it directly affects the product’s appearance, function and reliability. Applying correct lubrication to the machining zone can enhance the tribological characteristics of AL6061-T6 alloy. For further improvement, introducing nanolubricant may yield superior product quality due to the rolling action of nanoparticles at the tool-workpiece interface, which significantly reduces cutting force. In this research work, a nanolubricant containing MoS2 nanoparticles is developed for end milling of AL6061-T6 alloy and the surface morphology of the machined workpiece is investigated as well.

1. Introduction

Scientists have been recently seeking metals with excellent machining capability and desirable mechanical properties for aerospace applications. A very important metal employed in the aerospace industry is an Al-Mg-Si alloy, namely AL6061-T6. Beside aerospace, this alloy also finds use in the automotive, food packaging, railway, vehicles, bridges, offshore structure topsides and high-speed ship industries. The dominant mechanical properties of high strength, good weldability and light weight, are the main reasons for selecting this alloy. Therefore, to achieve desired product quality from it, machining with appropriate dimensional accuracy is necessary.

The surface roughness of a machined workpiece is an important parameter in industrial products. The demand for high quality draws attention to product quality, especially machined surface roughness, because it directly influences product appearance, function and reliability (Sayuti et al., 2012b). Cutting fluid is an essential component for achieving the required dimensional accuracy and high product quality during machining. Cutting fluid is applied due to the lubrication and cooling function it provides (Hamdan et al., 2011). Although the significance of lubrication in machining is widely recognized, cutting fluid application to machining is decreasing as it cause an environmental and health problems (Reddy et al., 2010). Using conventional cutting fluid (flood coolant) is responsible for a number of technoeconomic and environmental problems like environmental pollution, health problems to operators, water pollution, etc (Tan et al., 2002). The increasing request for higher productivity, product quality and decreasing cost in the manufacturing process involving machining is the main challenge industries are faced with (Kuram et al., 2013). On the other hand, the demand for high material removal rate, high stability and longevity of cutting tools has extensively grown (Fratila and Caizar, 2011). Besides, some researchers realize that the cost related to cutting fluid is frequently higher than that related to cutting tools (Tan et al., 2002). For many companies, the costs associated with cutting fluid are much higher than overall machining costs.
In addition, a considerable portion of energy is converted into heat due to the friction between the tool and workpiece in the machining zone in the machining process. Heat generated during machining is critical in terms of workpiece quality, as it directly affects product quality at the tool-workpiece interface (Cetin et al., 2011). In general, the heat produced during machining is considered critical in terms of workpiece quality (Hanafi et al., 2012). Thus, effective control of heat generated in the cutting zone is essential to ensure good surface quality throughout machining (Lawal et al., 2013). Applying cutting fluid influences machining performance through lubricating and cooling actions (Attanasio et al., 2006). The development of governmental pollution prevention initiatives and increasing consumer focus on environmentally friendly products has put increased pressure on industries to minimize the use of cutting fluids (Sarhan et al., 2011).

Industries and researchers are striving to decrease the utilization of lubricants in metal cutting processes for improved safety, less environmental pollution and economic benefits. It has been reported that compared to conventional lubrication, the minimal quantity lubrication (MQL) system in turning provides additional advantages in terms of tool wear reduction. For dry and wet machining processes, MQL has shown vast development in cutting forces, tool life, cutting temperature and surface finish (Barczak et al., 2010). In MQL, the lubricant is directly applied at the cutting zone, which significantly improves the machining process and has the additional benefits of higher cutting speeds and feed rates (Fratila, 2009). In this regard, nanoparticles suspended in lubricant make an attractive and innovative solution (HE, 1982). Many lubricants containing nanoparticles are deemed advantageous in modern technology, as they are capable of sustaining and providing lubricity over a wide range of temperatures (Nakamura et al., 2000).

Nanoparticles suspended in lubricant are a novel engineering material consisting of nanometer-sized particles scattered in a base fluid. It is an effective method of reducing the friction between two contact surfaces through the effect of rolling nanoparticles. However, nanoparticles are expected to be able to sustain high temperatures during machining, in addition to non-toxicity, ease of applicability and cost effectiveness. Nanolubricant effectiveness depends on morphology, crystal structure, size, quantity and the way nanoparticles are introduced to the tool-workpiece interface (Alberts et al., 2009).

Labor and materials associated with preserving lubricant and equipment integrity decrease consequent to the high performance of nanoparticle-based lubricants. Moreover, productivity in the machining industry may be amplified through cost reduction by decreasing cutting fluids, better environmental safety and improved machining properties. It is essential to consider the health and environmental issues when dealing with lubricant materials.

A physical analysis of nanolubricant showed that nanoparticles can easily penetrate into the rubbing surfaces and have considerable elastohydrodynamic lubrication effect (Peng et al., 2009). As an example, the friction coefficient of a nanolubricant containing fullerene for an orbiting plate in sliding thrust bearings is much less than that of conventional lubricant oil. It is understood that fullerene nanoparticles enter between friction surfaces and enhance the lubricating performance by increasing the viscosity and preventing direct metal surface contact (Lee et al., 2009). Simulation results also showed that tool wear rate is significantly reduced when interface adhesive strength diminishes (Wenlong et al., 2011). On the other hand, in the context of nanoparticle concentrations, it was found that nanolubricant thermal conductivity increases almost linearly with concentration, which produces hydrodynamic interactions that enhance thermal transport capability (Murshed et al., 2009).

To investigate machining performance, several types of nanoparticles have been used, such as silicon dioxide, graphite, fullerene, etc. Due to excellent lubricity, molybdenum disulfide (MoS2) is widely utilized in lubricants, composite materials and grease. The weak Van der Waals force results in effortless sliding between two S–Mo–S layers. Compared with bulk MoS2, nano-sized MoS2 usually has better tribological properties (Hu et al., 2011). Also, MoS2 nanoparticles are identified as a hard and brittle material easily found on the market in a wide range of sizes. Graphite and MoS2 are among the most common lubricants due to their layered morphology and crystal structure. Their morphology consists of hexagonally arranged carbon atoms that form planar lattice structures due to strong covalent bonds.

The application of MoS2 nanoparticles suspended in mineral oil has not been well investigated as a cutting fluid, especially in terms of machined surface quality and morphology. In this paper, the authors explore the development of MoS2 lubricant meant to assist machining performance. It is reported that cutting force and power consumption may be reduced considerably, and consequently surface quality would be enhanced by the nanolubricant with its billions of rolling elements working in the tool chip interface.

![Fig. 1. Experimental set-up.](image-url)
Therefore, in this research the aim is to investigate the surface quality and morphology of AL6061-T6 alloy during the milling operation by employing MoS2 nanolubricant, while the MQL system is used to deliver and induce MoS2 nanolubricant into the tool–chip interface.

2. Experimental set up and procedure

Experiments were carried out using the setup illustrated in Fig. 1. A vertical type machining center (Mitsui Seiki VT3A) was utilized for the milling process. The spindle has constant position preloaded bearings with an oil-air lubrication system having maximum rotational speed of 20,000 min\(^{-1}\) and 15 kW power. The slot-milling test was done on a rectangular aluminum alloy (AL6061-T6) workpiece of 40 × 40 × 100 mm\(^3\).

Table 1 provides the mechanical properties of the workpiece material. End milling was carried out with a tungsten carbide (AE302100) tool that had 2 flutes with 10 mm diameter. The tool moved in the \(+X\) direction to cut 100 mm strokes; the workpiece and its tool paths are illustrated in Fig. 2. The cutting speed, feed and depth of cut were 5000 min\(^{-1}\), 100 mm/min and 5 mm respectively, which were selected based on the tool manufacturer’s recommendations. The two lubrication types employed in this investigation were ordinary lubricant and nanolubricant. The ECOCUT HSG 905S from FUCHS served as the base oil in both modes of lubrication. This oil is free from phenol, chlorine and other additives. The nanolubricants were prepared by mixing MoS\(_2\) nanoparticles (average particle size of 20–60 nm) with the mineral oil followed by sonication (240W, 40 kHz, 500W) for 48 h in order to homogenously suspend the nanoparticles in the mixture. The mechanical properties of MoS\(_2\) are presented in Table 2. The concentrations of MoS\(_2\) nanoparticles in base oil were 0.0, 0.2, 0.5 and 1.0 wt%. In case of 0.0 wt% concentration, it was a purely MQL process.

In economic terms, for 1 L of ordinary lubricant it would cost around 6.25USD, while for nanolubricant with 0.5 wt% MoS\(_2\) concentration, it would cost roughly 6.41USD. Although the price is a bit higher (2.5%) than when using ordinary lubricant, nanolubrication is unavoidable, especially in heavy duty machining where ordinary lubricant cannot withstand the high contact pressure and temperature.

The lubricants were delivered to the tool–chip interface region via minimum quantity lubrication (MQL). Experimentation was accomplished by using a thin-pulsed jet nozzle developed in the laboratory, which can be controlled by a variable pressure and speed control drive. The nozzle was equipped with an additional air nozzle to accelerate the lubricant into the cutting region and decrease the amount of lubricant fed by up to 25%. The nozzle system was placed in a flexible and portable junction connected to the machining spindle. The nozzle may be set at 60° on the machining spindle without interfering with the tool or workpiece during the machining process. The nozzle’s orifice diameter was 1 mm and the MQL oil pressure was set to 20 MPa with a delivery rate of 30 ml/min. The air pressure and nozzle orientation were set

<table>
<thead>
<tr>
<th>Ultimate tensile strength (MPa)</th>
<th>260</th>
<th>310</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Proof stress (MPa)</td>
<td>240</td>
<td>275</td>
</tr>
<tr>
<td>Hardness Vickers (HV)</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Mechanical properties of aluminum (AL6061-T6).

<table>
<thead>
<tr>
<th>Type</th>
<th>MoS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>Hexagonal-Layered</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1185</td>
</tr>
<tr>
<td>Density (g/cm(^3))</td>
<td>4.8–5.0</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>160.06</td>
</tr>
<tr>
<td>Color</td>
<td>Lead Gray to Black</td>
</tr>
<tr>
<td>Thermal conductivity at 300 K (W/cm-K)</td>
<td>0.014</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.03–0.06</td>
</tr>
<tr>
<td>Hardness (Mohs Scale)</td>
<td>1–1.5</td>
</tr>
</tbody>
</table>

Table 2 The mechanical properties of MoS\(_2\).
at 4 bars and 60 °C according to previous experiments, to achieve the best surface roughness. Fig. 3 presents the schematic sketch of the nozzle.

3. Experimental results and discussion

3.1. Surface roughness

The surface roughness ($R_a$) was measured after each machining run with a surface profilometer (Mitutoyo SJ-201) in three regions of the machined surface, and the average was plotted (Fig. 4). It is clear that with varying nanoparticle concentrations different surface roughness values was generated. The lowest surface roughness was evidently obtained at 0.5 wt% MoS$_2$ nanoparticle concentration. However, when the concentration was increased to 1wt% the surface quality declined.

To investigate the reasons behind these findings, the machined surface morphology was assessed under field emission scanning electron microscope (FESEM). The structure’s phase and arrangement was characterized by X-ray diffraction (XRD) analysis. For sample preparation, parts of the machined surface were cut with a wire cutting machine of 15 mm × 15 mm × 5 mm. The parts were cleaned in distilled water and chemicals to remove surface contamination.

**Fig. 5.** FE-SEM on samples (a), (b), (c) and (d) which machined with 0, 0.2, 0.5 and 1.0 Wt% concentration of MoS2 respectively.
3.2. The morphology of the surface machined using MoS2 nanolubricant

FESEM and X-ray diffraction (XRD) were employed to examine the morphology and phase of the machined surface. FESEM provides topographical and elemental information at various magnifications, with a virtually limitless depth of area. It is possible to examine smaller-field impurity spots at electron accelerating voltages compatible with energy dispersive spectroscopy. Also, FESEM captures high-quality images with negligible electrical charging of samples. XRD is mainly useful for identifying fine-grained minerals and their mixtures, which cannot always be analyzed by other techniques. While XRD analysis provides the quantitative volume fractions of minerals in a sample, these samples are small and can be high-graded intentionally or accidentally. The important result pertains to which minerals are present, with less emphasis on the quantity of each mineral.

To prepare the surface, cleaning is necessary to remove all undesirable surface particles prior to using FESEM and EDX. To eliminate minor contamination, the surface was etched with hot sodium hydroxide solution. The remaining surface oxides, which were combinations of inter metallic, metal and metal oxides, were removed using an aqueous solution containing an oxidizing inorganic acid, phosphoric and sulfuric acids, simple and complex fluoride ions, organic carboxylic acid, and manganese in its oxidation state.

3.2.1. FESEM analysis

FESEM images of the machined surfaces are shown in Fig. 5 for four different MoS2 concentrations. The results indicate that MoS2 nanoparticles were dispersed in the cutting zone by the high-pressure air stream. This technique improved the machined surface morphology. The atomized mist of MoS2 nanoparticles ensured efficient nanolubricant supply into the cutting zone compared with conventional lubrication methods. As per Fig. 5(b–d), protective thin films containing billions of MoS2 nanoparticles were produced on the feed marks of the machined surface. The protective films facilitated much less friction and thermal deformation compared to bare surface. Thin film formation amplified when the concentration of MoS2 nanoparticles was increased from 0.2 to 0.5 wt%. However, a further increase in concentration up to 1.0 wt% led to less protective films compared to the 0.5 wt% concentration. This outcome is in total agreement with the lowest surface roughness results obtained at 0.5 wt% MoS2 nanoparticle concentration (Fig. 4). Also, when nanoparticle concentration was increased to 1 wt% the surface quality declined.

The increment of nanoparticle concentration in lubricant increased the cutting oil viscosity. In this case, more nanoparticles existed in the tool-workpiece interface, which served as spacers, eliminating the friction between the tool and workpiece. Nanoparticles suspended in lubricant have filler and polisher effects. Consequently, nanolubricants produce the best surface finishes. It has also been proposed that since nanoparticles roll like microspheres at the tool-workpiece interface, the frictional coefficient may be reduced (Liu et al., 2004). Nanoparticle appearance and specifications, such as size, shape and concentration are factors that control the frictional behaviors. It is worth noting that the nanoparticles in this work ranged from 2 to 60 nm. Smaller nanoparticles reduced friction more effectively by forming a protective film at the surface.

Other researchers have shown that in thin film contacts, colloidal nanoparticles penetrate into the elastohydrodynamic contacts by mechanical entrapment means (Wu et al., 2007). The high contact resistance in addition to the extreme pressure at the cutting zone induces the formation of a chemical reaction layer on the workpiece surface. Large amounts of heat generated in the cutting zone alter the elastohydrodynamic lubrication to boundary lubrication. This phenomenon results in the formation of thin protective films on surfaces, as seen in Fig. 5.

It is believed that nanoparticles deposited onto the friction surface compensate for the loss of mass, which is called "mending effect" (Liu et al., 2004). Due to the porous nature of spherical MoS2 nanoparticles, the high elasticity potentially imparted, augments their resilience in a specific loading range and enhances the gap at the tool-workpiece interface (Zhang et al., 2011). When nanofluid is dispersed in the cutting zone, a number of particles get embedded into the machined surfaces during machining. Some particles have a rolling effect while others are sheared from the very high pressure...
Fig. 7. X-ray Diffraction (XRD) on samples (a), (b) and (c) under machining with 0.2, 0.5 and 1 wt % concentration of MoS2 nanoparticles, respectively.
in the cutting zone. Nanoparticle shape changed under high compression (Fig. 6). With increasing MoS2 nanoparticle concentration, the extent of shape change and shearing were more intense. Some of the nanoparticles were partially ejected by other nanoparticles that left the nozzle into the cutting zone. As a result, nanoparticles could be supplied to the contact spots without being broken. The ploughed-off nanoparticles left thin exfoliated film on the contact spot due to high loading damage (Rapport et al., 2005).

Meanwhile, at higher concentrations, the nanoparticles that filled the surface cavity were sheared off by other nanoparticles. With this mechanism, a lubrication film was formed and the surface was polished with better quality (Rapport et al., 2002).

Though when the nanoparticle concentration continued to rise to 1.0 wt%, the surface finish was inferior compared to 0.5 wt% concentration. At higher quantities, nanoparticles impregnated the surface pores. These nanoparticles were then sheared off by other incoming nanoparticles, and more ploughed-off particles remained on the thin exfoliated film. Therefore, the 1.0 wt% concentration provided poorer surface quality compared to 0.5 wt%. Thus, as shown in Fig. 4, the concentration of 0.5 wt% provided the optimum machined surface morphology when nanolubricant was used during machining. The machining of AL6061-T6 alloy with nanolubricant containing 0.5 wt% MoS2 improved the surface roughness by 3.87% compared with pure oil in an ordinary machining process. For additional investigation, the substrate surface was analyzed by X-ray diffraction (XRD) as seen in Fig. 7.

3.2.2. XRD analysis

The XRD analysis (Fig. 7) demonstrates the existence of 1.1, 3.3 and 0.5 wt% MoS2 nanoparticles on the machined surface when the workpiece was milled by nanolubricants containing 0.2, 0.5 and 1 wt% MoS2. These results fully support the FESEM outcome, as the highest percentage of residual MoS2 was obtained from the workpiece milled with nanolubricant containing 0.5 wt% MoS2 nanoparticles. It is also clear that when nanoparticle concentrations continued to increase up to 1.0 wt% the residual content of MoS2 was the lowest.

4. Conclusions

In this investigation, the effects of MoS2 nanoparticles suspended in nanolubricant on the machined surface morphology were studied. The nanolubricants were prepared by suspending MoS2 nanoparticles (20–60 nm) in base oil (ECOCUT HSG 905S). The mixtures were stirred for 48 h, followed by ultrasonication for 48 h. To supply the nanolubricant to the cutting zone and decrease oil consumption, an MQL system with a nozzle having an orifice diameter of 1 mm was adopted. The cutting experiments were carried out on an aluminum alloy (AL6061-T6) workpiece. To accelerate the lubricant into the tool-workpiece interface, pressured air was used, which too, led to less nanolubricant consumption and optimal surface morphology. The presence of MoS2 nanoparticles in the tool-workpiece interfaces improved the quality of the machined surface. Using nanolubricant in AL6061-T6 milling produced fine machined surfaces owing to the function of the suspended nanoparticles. Having MoS2 nanoparticles in the tool-workpiece interface enhanced the machined surface due to the rolling, filling and polishing actions at the tool-workpiece interface. According to the experimental results, machined surface quality was superior when nanoparticles of 0.5 wt% concentration were applied as opposed to pure oil or other nanoparticle concentrations. Finally, it can be concluded that MoS2 suspended in nanolubricant is an excellent alternative for achieving ideal surface quality. For future work, research to investigate the potential and feasibility of MoS2 application in the die and mould, as well as the automotive and aerospace industries, should be sustained.

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References


