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ORIGINAL ARTICLE

Investigating the optimum molybdenum disulfide (MoS_2) nanolubrication parameters in CNC milling of AL6061-T6 alloy

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Abstract Aluminum 6061-T6 is an important alloy as it has dominant mechanical properties like weldability and hardness, and has the potential to be used at variable temperatures. AL6061-T6 is frequently used in the aerospace industry, as well as aircraft, automotive, and packaging food industries. Milling of Al6061-T6 is important especially to produce various product shapes for adapting to diverse applications. The aptitude of the CNC milling machine for batch production would be a noteworthy advantage. However, the demand for high quality brings attention to product quality, particularly the roughness of the machined surface because of its effect on product appearance, function, and reliability. Introducing correct lubrication to the machining zone could improve the tribological characteristics of Al6061-T6. For additional improvement, applying nanolubrication may produce superior product quality, as the rolling action of billions of nanoparticle units in the tool chip interface can significantly decrease the cutting forces. In this research work, the optimum MoS_2 nanolubrication parameters in Al6061-T6 milling to achieve the lowest cutting force, cutting temperature and surface roughness are investigated. The parameters include nanolubricant concentration, nozzle orientation and air carrier pressure. Taguchi optimization along with standard orthogonal array $L_{16}(4^3)$ are employed. Furthermore, surface roughness and cutting force are analyzed via signal-to-noise (S/N) response analysis and the analysis of variance (Pareto ANOVA) in the hopes of achieving optimum conditions and to determine which process parameters are statistically significant. Finally, optimization improvements are investigated through confirmation tests.

Keywords MoS_2 nanolubrication · End milling · Surface roughness · Cutting force · Al6061-T6 alloy

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1 Introduction

Aluminum has advantages above other materials comprising a high strength/weight ratio, corrosion resistance and formability. Alloys 6061, 7075, and 2024, sometimes referred to "aerospace alloys" due to their partial applications in the aeronautics industry. These alloys are engineered to be lightweight and strong. Their ease of formability allows complex shapes and parts to be drawn, which can then be further enhanced with heat treatment. Aluminum AL6061-T6 is an alloy which contains magnesium and silicon as major alloying elements, and commonly serves several purposes due to the superior mechanical properties such as hardness and good weldability [1, 2] as well as the solutionized and tempered-grade characteristic of this type of aluminum. Widespread applications for this type of material are found in the aircraft, automotive, and food packaging industries. The capability of the CNC milling machine to produce intricate, special products may be a noteworthy advantage for aluminum AL6061-T6. However, the demand for high quality brings attention to a product's quality and surface condition, especially machined surface roughness — because of its effect on product appearance, function, and reliability [3, 4].

The tribological characteristics of the machining process can be improved by introducing lubrication into the

machining regions [5, 6]. Applying lubrication correctly reduces friction at the tool–chip interface, resulting in enhanced surface quality. Despite the significance of lubrication in machining being widely recognized, conventional flooding application in machining processes has become a huge liability. Such fluids are difficult to dispose of, expensive to recycle and can cause skin and lung diseases to operators. The increasingly stricter environmental regulations and enforcement are also eliminating much of the flexibility with using cutting fluids [7, 8]. Moreover, from an economical perspective, the costs associated with the usage of lubricants is estimated to be several billion US$ yearly. The cost related to lubrication and cutting fluid is 17 % of the total production cost, which is normally higher than that of cutting tool equipment which incurs only 7.5 % of the total cost. Consequently, eliminating lubricants if possible may be a significant economic incentive [9, 10].

Lubrication research is deemed to increase in response to a demand for it. In the past, demand arose when new technologies posed new challenges, e.g.,*** space stations, adiabatic diesel engines, and ultra-high storage density in magnetic hard disks. Such new technologies pose a burden outside the existing knowledge base, such as high temperatures, radiation, and nanometer scale precision [4]. At present, countless efforts are being made to develop advanced machining processes using less lubrication [11]. A promising alternative to conventional flood coolant applications is minimum quantity lubrication (MQL). Klocke and Eisenblätter [12] stated that MQL refers to only a minute amount of lubrication used — typically, a flow rate of 50 to 500 ml/h, or about 3 to 4 orders of magnitude lower than the amount normally used in flood cooling conditions. This has been reported to reduce friction, cutting temperature and improve tool life due to the lubricant's ability to penetrate into the chip–tool interface, thus improving the product's surface quality. However, the respective surface quality improvement is a function of the MQL lubrication parameters that include air pressure and nozzle angle (better known as lubrication factors system). The MQL system is adjusted according to these parameters to deliver lubricant. For further improvement, introducing nanolubrication could produce much better product quality as the rolling action of billions of units of nanoparticles in the tool–chip interface could notably reduce cutting forces. The structure, shape and size of nanoparticles play an important role in their tribological properties [13, 14]; however, nanoparticle concentration in oil is an essential parameter for investigation to determine the optimum surface quality.

Up to now, several nanolubricants have been identified by advancements in modern technology — nanolubricants which can sustain and provide lubricity over a wide range of temperatures [15, 16]. The effectiveness of lubrication is dependent on quantity, the morphology and crystal structure of solid lubricants, and the way that particles get introduced to the tool–workpiece interface [17]. Nanolubricants comprise a kind of new engineering material consisting of nanometer-sized particles distributed in base oil. It is potentially an effective method to reduce friction between two contact surfaces, depending on the working conditions. Lubricants are expected to withstand the high machining temperatures, and be non-toxic, easy to apply and cost-effective [18]. On the other hand, physical analysis of nanolubricants [19] demonstrates that dispersed nanoparticles can easily penetrate into the rubbing surfaces and have a large elastohydrodynamic lubrication effect. According to researchers, under a single-thrust bearing tester the nanolubricant's coefficient of friction is less than that of pure oil while the extreme pressure of the nanolubricant is two times higher than that of pure oil; hence it can be deduced that the nanolubricant improves lubrication performance by averting contact between the metal surfaces. Moreover, the thermal conductivity of a nanolubricant increases linearly with the concentration, thus facilitating hydrodynamic interaction to enhance thermal transport capability [20–23].

Molybdenum disulfide (MoS_2) nanoparticles make a hard, brittle material that is cheap and readily available on the market. MoS_2 possesses excellent mechanical properties especially in terms of hardness. Size ranges from 20 to 100 nm, and the ideal range to be used in machining applications is 20 to 60 nm, as it could be easily and effectively accelerated by an MQL system into the machining zone [21].

In this study the authors are investigating the optimum molybdenum disulfide (MoS_2) nanolubrication parameters in CNC milling of AL6061-T6 alloy to achieve the best surface quality, lowest cutting force and lowest cutting temperature. These parameters include nanolubricant concentration, nozzle orientation and pressurized air (hereafter called control factors). The conventional technique to optimize this process is the "trial and error" approach, yet it is very time consuming due to the requirement of a large number of experiments. Hence, a reliable systematic approach for optimizing machining parameters is necessary. Taguchi optimization is an efficient, effective, reliable and simpler approach, in which the response parameters affecting surface roughness, cutting forces and cutting temperature can be optimized [24]. The stages in the Taguchi optimization method include: selecting the orthogonal array (OA) according to the numbers of controllable factors, running experiments based on the OA, analyzing data, identifying the optimum parameters, and conducting confirmation runs with the most favorable levels of all parameters.

2 Experimental design

The standardized Taguchi method was employed according to the experimental design of an $L_{16}(4^3)$ OA in order to achieve