Int J Adv Manuf Technol (2013) 67:833–849
DOI 10.1007/s00170-012-4527-z

ORIGINAL ARTICLE

An investigation of optimum SiO_2 nanolubrication parameters in end milling of aerospace Al6061-T6 alloy

M. Sayuti · Ahmed A. D. Sarhan · M. Hamdi

Received: 16 December 2011 / Accepted: 24 September 2012 / Published online: 9 October 2012

Abstract Aluminium AL6061-T6 is a common alloy which is used for many purposes since it has the superior mechanical properties such as hardness and weldability. It is commonly used in aircraft, automotive and packaging food industries. Milling of Al6061-T6 would be a good process especially in producing varieties shape of products to adapt with different applications. The capability of the CNC milling machine to make batch production would be a noteworthy advantage. However, the demand for high quality focuses attention on product quality, especially the roughness of the machined surface, because of its effect on product appearance, function and reliability. Introducing correct lubrication in the machining zone could improve the tribological characteristic of Al6061-T6 leading to higher product quality. In this research work, the optimum SiO_2 nanolubrication parameters in milling of Al6061-T6 are investigated to achieve correct lubrication conditions for the lowest cutting force, cutting temperature and surface roughness. These parameters include nanolubricant concentration, nozzle angle and air carrier pressure. Taguchi optimization method is used with standard orthogonal array $L_{16}(4)^3$. Furthermore, analyses on surface roughness and cutting force are conducted using signal-to-noise (S/N) response analysis and the analysis of variance (Pareto ANOVA) to determine which process parameters are statistically significant. Finally, confirmation tests were carried out to investigate the optimization improvements.

Keywords End milling · SiO_2 nanolubrication · Surface roughness · Cutting force · Al6061-T6 alloy

M. Sayuti · A. A. D. Sarhan (✉) · M. Hamdi
Centre of Advanced Manufacturing and Material Processing,
Department of Design and Manufacturing, Engineering Faculty,
University of Malaya,
50603, Kuala Lumpur, Malaysia
e-mail: ah_sarhan@yahoo.com

M. Sayuti
e-mail: mdsayuti@siswa.um.edu.my

M. Hamdi
e-mail: hamdi@um.edu.my

A. A. D. Sarhan
Department of Mechanical Engineering, Faculty of Engineering,
Assiut University,
Assiut 71516, Egypt

1 Introduction

Aluminium has many benefits over other materials, including a high strength-to-weight ratio, corrosion resistance, formability and price. Alloy 6061, 7075 and 2024 are sometimes referred to the group of "Aerospace Alloys" for their practical applications in aviation industry. Theses alloys are engineered to be lightweight and strong, and their ease of formability allows complex shapes and drawn parts [1], which can then be further enhanced with heat treating. Aluminium AL6061-T6 is an alloy which contains magnesium and silicon as major alloying elements. It has been a common alloy which is used for many purposes since it has the superior mechanical properties such as hardness and good weldability [2, 3]. This is due to solutionize and tempered grade that belong to this type of aluminium. The common applications for this kind of material are in aircraft industry, automotive industry and packaging food industry. The capability of the CNC milling machine to make complicated special products would be a noteworthy advantage for aluminium AL6061-T6. However, the demand for high quality focuses attention on the surface condition and the quality of the product, especially the roughness of the machined surface, because of its effects on product appearance, function and reliability [4, 5].

The tribological characteristic of machining process can be improved by introducing lubrication in the machining zone [6, 7]. Correct application of lubricants has been proven to greatly reduce friction in the tool–chip interface; this results in improving the surface quality. Although the significance of lubrication in machining is widely recognized, the usage of conventional flooding application in machining processes has become a huge liability. Not only does the Environmental Protection Agency regulate the disposal of such mixtures but many countries and localities also have classified them as hazardous wastes as they contain environmentally harmful or potentially damaging chemical constituents. These fluids are difficult to dispose and expensive to recycle and can cause skin and lung disease to the operators. Also the increasingly stricter environmental regulations and their enforcement are eliminating much of the flexibility in the use of cutting fluids [8, 9]. Beside that economically, the costs associated with the use of lubricants is estimated to be several billion dollars per year. The cost related to the lubrication and cutting fluid is 17 % of total production cost which is normally higher than that of cutting tool equipments which incurs only 7.5 % of total cost. Consequently, eliminating the use of lubricants, if possible, can be a significant economic incentive [10, 11].

At present, many efforts are being undertaken to develop advanced machining processes using less lubrications [12]. Promising alternatives to conventional flood coolant applications are the minimum quantity lubrication (MQL). Klocke and Eisenblätter [13] state that MQL is referred to the use of lubrication of only a minute amount—typically of a flow rate of 50 to 500 ml/h which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. This has been reported to reduce friction, cutting temperature and improved tool life due to its ability to penetrate into the tool–chip interface which improves the product surface quality. In addition, the dry chips can be recycled without incurring large cleaning expenses making the application of nanolubrication a plausible solution [9, 11, 14].

Nowadays, many nanolubricants have been identified by the advancement in modern technology which makes possible to sustain and provide lubricity over wide range of temperature [15, 16]. Nanolubricant is a kind of new engineering material consisting of nanometer-sized particles dispersed in base oil. It would be an effective method to be used in reducing friction between two contact surfaces and depends on the working conditions. Lubricants are expected to withstand the high machining temperatures, non-toxic, easy to be applied and effective in terms of cost [17]. The effectiveness of the lubrication depends on the morphology, crystal structure of solid lubricants, the way of particle introduced to the tool–workpiece interface and quantity [18].

Due to high performance of the nanoparticle-based lubricants, labour and materials associated with preserving lubricant and equipment integrity soon will be minimized. Health and environmental concern need to be addressed when dealing with lubricants materials. In addition, the productivity in the machining industry could increase through cost reduction by abandonment of the cutting fluid, saving the environment and at the same time improve the machining performance. Physical analysis of nanolubricant [19] showed that the nanoparticle dispersed can easily penetrate into the rubbing surfaces and have large effect of elastohydrodynamic lubrication. Under single thrust bearing tester, researchers reported that the coefficient of friction of nanolubricant is less than pure oil, and the extreme pressure of nanolubricant is two times higher than that of pure oil; hence, it can be concluded that nanolubricant improved the lubrication performance by preventing contact between the metal surfaces. Moreover, thermal conductivity of nanolubricant increases linearly with the concentration, which performs a hydrodynamic interaction to enhance thermal transport capability [20–23].

Many types of nanoparticle have been used as a lubricant by researchers in order to investigate its effects on the machining performance. It is well documented that silicon dioxide (SiO_2) nanoparticle is a hard and brittle material and cheap and available in market. This nanoparticle has very good mechanical properties especially in terms of hardness (Vickers hardness—1,000 kgfmm^{-2}) and available in very small size range from 5 up to 100 nm. The nanoparticles in the mineral oil would act as a combination of rolling and sliding bearings at the tool–chip interface. This, in turn, reduces the coefficient of friction significantly; hence, the lower cutting force can be obtained [24]. The reduction of cutting force leads to a better performance of the machining process [25]. However, the application of SiO_2 material with suspended in pure oil has not been well reported in improving the machining performance. Therefore, this research attempted to investigate the performance of SiO_2 as nanolubrication in end milling process of Al6061-T6 alloy.

In line with the previous research work as reviewed above, the investigation of optimum SiO_2 nanolubrication parameters in milling of Al6061-T6 is needed to focus on effective improvement of the machined surface quality by minimizing the cutting force and cutting temperature. These parameters include nanolubricant concentration, nozzle angle and air carrier pressure (hereafter called control factors). The conventional method to determine the optimal values of these parameters is to use the "trial and error" approach. However, due to the large number of experiments, the "trial and error" approach is very time-consuming. Hence, a reliable systematic approach to optimize these parameters is thus required.

The optimization method presented in this study is an experimental process called the Taguchi optimization method. Taguchi optimization, developed by Dr. Genichi