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Influence of Ranque-Hilsch vortex tube and nitrogen gas assisted MQL in precision turning of Al 6061-T6

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ABSTRACT

Dry machining is undesirable to produce precision surface due to thermal adversities especially for a low melting point material such as Al 6061-T6. Likewise, the conventional flood cooling is neither economically viable nor eco-friendly. In this context, three novel cooling-lubrication (C/L) technologies namely the nitrogen gas cooling (NGC), nitrogen gas assisted minimum quantity lubrication (NGMQL) and Ranque-Hilsch vortex tube (RHVT) NGMQL are investigated along with the air cooling (AC) in turning with an attempt to reduce surface roughness (R_a) and tool flank wear (VB_{max}). The machining was conducted using uncoated WC insert at two-levels of cutting speed and feed rate; and, as medium of cooling/lubrication the nitrogen gas and/or canola oil is employed. The SEM and 3D topographic images were analyzed for the machined surfaces, worn tool surfaces and chips. Results showed that the RHVT-NGMQL revealed the least surface roughness and tool wear (~75% improvement compared to other C/Ls). Notable wear modes were: in dry cutting the plastic deformation, BUE and adhesion; in NGC the BUE; in NGMQL the rubbing and adhesion; in RHVT-NGMQL the adhesion. In micro-level, no significant difference in chip structure was found for the studied C/L methods In addition, the Composite Desirability optimization was adopted to systematically minimize R_a and $VB_{\max}$ concurrently. It was found that the optimum speed v_c = 160 m/min and feed rate f = 0.06 mm/rev under RHVT-NGMQL C/L condition has the potential to generate a precision surface with a roughness value < 1.0 µm.

1. Introduction

The aluminum alloy Al 6061-T6 has notable applications in automobile and aerospace industries owing to its high strength but low weight, corrosion resistance, and thermal stability [1]. A stringent requirement on surface finish is required for such intricate applications from this hardened alloy. But the localized heat concentration triggered by the tool tip when inscribed inside work material to cause chip shearing is the prime reason of thermal softening. This effect is more prominent in machining of a material that has a low melting temperature such as aluminum alloy. In particular, the capability of such machining operation to generate precision surface is compromised. Consequently, the acceptability of that machining process becomes restricted too.

The machinability investigation of Al 6061-T6 has been explored by researchers. For instance, Sayuti et al. [2] investigated the machinability of this alloy using SiO_2 nano-lubricant − a variation was maintained in concentration of lubricant. They stressed that the used lubricant formed a thin layer which ensured a better surface quality, and also reduced the cutting force and temperature. In another study, Sayuti et al. [3] optimized the machining parameters for optimum level of cutting force and surface roughness for milling of Al 6061-T6. Then, Xu et al. [4] presented the study of chip formation indices in machining of Al 6061-T6 alloy for orthogonal cutting at high-speed. They modeled and investigated the chip shape, chip thickness, shear angle, chip-tool contact length, chip-shear distance etc. Besides, Wang et al. [5] examined the influence of cutting speed, feed rate and depth of cut on heat generation in ultra-precision machining of Al 6061 alloy. Rahmati et al. [6] studied the role of MoS_2 nano-lubricant in end milling of Al 6061-T6 alloy. The input variables were the concentration of lubricant, orientation of nozzle and the air pressure. In addition, the optimization was performed using Taguchi method. Kamguem et al. [7] machined three grades of Al alloy using two different coated tools with a hope to improve the surface quality. TiCN was found to provide the best surface

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finish. However, surface roughness was mostly affected by the feed rate. Camposeco-Negrete [8] successfully presented the power consumption parameters in machining of Al 6061-T6 alloy and its relevance with the surface roughness. Later, Camposeco-Negrete [9] optimized the machining parameters for the same material in order to make higher surface quality, better productivity and lower power consumption. Ooi et al. [10], for precision machining of Al 6061-T6 alloy, developed a fuzzy-rule based model to predict the surface roughness, temperature and force in milling process. It seems that for such a lucrative material, the conducted studies are insufficient, and more studies are required – especially for turning of Al 6061-T6.

In turning process, the surface roughness is primarily noted along the direction of feed movement. Along this direction, the roughness profile is predominantly afflicted by the tool wear, tool tip breaking, inclusion of foreign material on work surface, built-up-edge, burr formation on machined surface, existence of cracks and the vibration. All together, due to these factors the actual roughness profile deviates from theoretical surface roughness [11]. In such cases, most of these factors are directly related to cutting zone temperature. In dry cutting condition, the cutting region is highly heated, mostly due to the shearing of materials, friction and plastic deformation. Though some authors have stressed that dry machining can be a performance improver with special attention to process parameter optimization and appropriate tool selection [12], in general dry environment jeopardizes the machining performance. As the heat is the main culprit for such unacceptability, an instant heat removal from the machining zone is presumed to divulge an improved surface finish. However, conventional flood cooling (use of excessive coolant) was somewhat successful in diminishing the temperature, but in reality the machining performance is scarcely improved.

Recently, Minimum Quantity Lubrication (MQL) in machining is reported as a high performing mode of cooling – lubrication (C/L) [13]. The sprayed MQL when suspended as droplets and supplied in minute quantity under high pressure, upon hitting the hot work-tool-chip surfaces evaporates and subsequently reduces the temperature dramatically [14,15]. It was also stressed that these particles actively lubricated the faying surfaces, and augmented the surface finish qualities. The glorious implementation of MQL in machining of a wide range of materials is already available [16–22]. Nonetheless, the MQL performance can be further improved using Nitrogen gas atmosphere and Ranque-Hilsch vortex tube (RHVT), which is the demand of time to progress this coolant technology further. The former one has potential to ensure inertness; therefore, proneness to chemical reactions is expected to be reduced. While in later mode, an additional chilling is provided along with MQL.

To the best of author's knowledge there is no such study that presented the precision machining investigation of Al 6061-T6 alloy using Nitrogen Gas Cooling (NGC), Nitrogen Gas assisted Minimum Quantity Lubrication (NGMQL), and Ranque-Hilsch vortex tube (RHVT) Minimum Quantity Lubrication. To fill this gap, an attempt has been made here to investigate the machined surfaces in turning under aforementioned C/L conditions. Moreover, the cutting tool wear pattern and mechanism were examined. The SEM and 3D surface topography were used for these purposes, along with the study of generated chips. Finally, the desirability based optimization is performed to gain cutting parameter setting appropriate for precision turning.

2. Experimental conditions

That the Al 6061-T6 hardened Aluminum alloy has extensive usability in automobile, aerospace and marine industries due to its good corrosion resistance, high strength-to-weight ratio, lightness. Therefore, it has been taken as subject material, and machined in a CNC lathe (Model: Batliboi Sprint 20 TC; Spindle power of 11 kW; Spindle speeds of 30–4000 rpm). The chemical composition and mechanical properties of Al 6061-T6 are listed in Tables 1 and 2 respectively. The work sample had a length of 100 mm and a diameter of 32 mm. The uncoated tungsten carbide inserts (CNMG120404) with nose radius 0.4 mm, approach angle of 90°, rake angle of −6°, and clearance angle of 15° were used. Note that for each run, a new tool insert was used, and each machining run was conducted for 30 s.

Table 1
Chemical composition of work material.

Al Alloy	Cr	Cu	Mg	Mn	Si	Ti	Zn	Fe	Al
6061-T6	0.04	0.15	0.8	0.15	0.4	0.15	0.25	0.7	Balance

Table 2
Mechanical properties of work material.

Al Alloy	Vicker's Hardness	Tensile strength (MPa)	Thermal conductivity (W/mK)	Melting point (°C)
6061-T6	107	310	167	582–651

Table 3
Experimental conditions.

Category	Specification
Machine	Batliboi SPRINT 20 TC (11 kw)
Work material	Aluminium 6061-T6
Size	Length = 100 mm, Diameter = 32 mm
Cutting inserts	CNMG 120404 WIDIA
Cutting speed, v_c (m/min)	160 and 320
Feed, f (mm/rev)	0.05 and 0.15
Depth of cut, a_p (mm)	2
Cooling environment	AC, NGC, NGMQL, RHVT-NGMQL
Nitrogen gas flow rate	20 l/min
MQL supply	Nitrogen at 6 bar pressure, lubricant at 100 ml/hr flow rate
Nozzle to tool tip distance	45 mm

The machining was carried out in four cooling and lubrication conditions: Air Cooling (AC), Nitrogen Gas Cooling (NGC), Nitrogen Gas assisted Minimum Quantity Lubrication (NGMQL), Ranque-Hilsch Vortex Tube NGMQL (RHVT-NGMQL). The details of RHVT are delineated under Section 3. In MQL, canola oil is used as lubricant and 99.998% pure N_2 is used as carrier gas. Moreover, the used nozzle had an internal mixing system. More technical specifications are listed in Table 3. The schematic diagram of the experimental setup is outlined in Fig. 1.

The general full factorial method is adopted for deriving the machining runs. Using this method, 2-levels of cutting speed, 2-levels of feed, and 4-levels of C/Ls have revealed a total of 16 experimental runs (Table 4).

The C/L condition's performance was evaluated average surface roughness (R_a), maximum tool flank wear (VB_{max}), and chip formation. The R_a is the mostly used indicative parameter for precision turning, while the $VB_{\max}$ indicates the capability to produce a good surface and the machining economy. The flank wear was measured using the Leica DFC 290 tool maker's microscope (for a typical measurement of maximum flank wear, see Fig. 2) and the average surface roughness was measured using the Mitutoyo SJ 301 roughness tester. In addition, the Scanning Electron Microscopic (Jeol make) and 3D topographic analysis were conducted too.

3. Ranque-Hilsch vortex tube cooling mechanism

A vortex tube, also called a Ranque-Hilsch vortex tube, is a device that separates a stream of compressed air into a hot and cold stream. It has no moving parts although it functions like a refrigeration machine. Initially discovered by Ranque [23], the vortex tube was abandoned by