Effects of submerged convective cooling on turning of AZ31 magnesium alloy: Tool temperature and wear improvements

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Abstract

Low melting point and material adhesion are associated challenges of magnesium alloy, leading to extreme built-up edge (BUE) and built-up layer (BUL) formations during machining process. Dry machining is favourable for machining magnesium alloy. However, this strategy inflicts excessive adhesive wear on the cutting tool. Therefore, this current work focuses on application of an innovative cooling technique, known as submerged convective cooling (SCC) for the turning of AZ31 magnesium alloy. Prior to cutting experiment, a computational fluid dynamics (CFD) simulation was conducted to evaluate internal structure of cooling module. Based on the CFD simulation, a small inlet/outlet diameter of 3 mm significantly contributed to the reduction of the tool temperature, due to high heat transfer coefficient of cooling fluid in the SCC. From the experimental results obtained, it was evident that SCC at high cooling water flow rate of 130 mL/min effectively reduced the tool temperature, chip temperature and tool-chip contact length by approximately 50, 8 and 28%, respectively. Consequently, it improved the surface roughness by 37%, when compared with the dry cutting condition. Finally, both BUE and BUL were observed in dry and SCC conditions, but the severity of these wear mechanisms improved or decreased remarkably under SCC conditions.

Keywords: Machinability, Magnesium alloy, Internal cooling, Tool temperature, Wear.

Nomenclature

Ac	Cooling area (mm ²)	'n	Mass flow rate (kg/s)		
Atc	Tool-chip contact area (mm ²)	R_a	Arithmetic average (µm)		
a_p	Depth of cut (mm)	Re	Reynolds number		
BUE	Built-up edge	SCC	Submerged convective cooling		
BUL	Built-up layer	T _{in}	Fluid inlet temperature (°C)		
CFD	Computational fluid dynamics	T _{out}	Fluid outlet temperature (°C)		
c_p	Specific heat capacity (J/kg.K)	T_f	Mean fluid temperature (°C)		
D	Inlet diameter (mm)	T_s	Insert temperature (°C)		
d	Cavity depth (mm)	T_T	Thermocouple temperature (°C)		
f	Feed rate (mm/rev)	T_{TC}	Thermal camera temperature		
Н	Height of cooling module (mm)		(°C)		
HPC	High pressure cooling	V	Fluid inlet velocity (m/s)		
h	Convective heat transfer	V_c	Cutting speed (m/min)		
	coefficient (W/m ² .K)	ρ	Density (kg/m ³)		
L _c	Tool-chip contact length (mm)	μ	Dynamic viscosity (kg/m.s)		

MQL Minimum quantity lubrication

1. Introduction

Metal cutting is often associated with heat generation from the material deformation at the primary shear zone as well as friction surfaces of the tool and workpiece at the secondary cutting zone. Consequently, high temperature or heat generation at these zones significantly influences the tool wear mechanisms; namely, as abrasion, adhesion, diffusion and built-up

layer. Excessive amount of heat generation is a primary cause of accelerated tool wear that shortens useful tool life. In addition, heat conducted from the tool insert to the tool holder increases its temperature, which compromises the dimensional accuracy, machined surface quality and integrity. Conventionally, cutting fluid is utilized as a key approach to metal removal, reduce temperature and facilitate heat transfer at the cutting zone as well as removing the chip from the zone [1, 2]. Presence of cutting fluids during machining process results to substantial improvement on cutting tool and workpiece. This is an excellent practice, as it alleviates the effects of friction on the tool flank face and the machined surface, since cooling can be attained through dissipation and conduction of the generated heat. Thermal damage on workpiece material and cutting tools can be prevented through lubrication and cooling effect of the cutting fluid, consequently reducing the tool wear [3].

Despite the key functions of cutting fluids for machining process improvement, it also has a few drawbacks as subsequently elucidated. Firstly, the cost associated with the procurement of the cutting fluids is as high as 16 - 30 % of the total manufacturing costs [4]. Secondly, due to the non-biodegradable nature of the fluids, expensive treatments prior to disposal are mandatory, which lead to high maintenance and disposal costs of up to two-fold of the purchasing costs of cutting fluids [4, 5]. Thirdly, it has been reported that 80% of occupational skin diseases, respiratory ailments and cancer diseases among the machine operators are caused by inhalation of the cutting fluids [6]. Hence, the importance of sustainable manufacturing emerges to alleviate the aforementioned drawbacks on the machining processes, environmental and their associated costs. These are the reasons why the use of dry cutting has great advantages and can be a favorable option.

Moving forward, dry cutting is an eco-friendly approach that supports reduction of harmful wastes and discharges. Eliminating the use of cutting fluids is possible through dry machining, as it promotes low processing cost and ecological hazard [7]. However, commercial and

practical applications of dry machining are uncertain, because of the absence of cooling and lubrication at tool-workpiece interface [8]. Excessive frictions at the tool-workpiece interfaces also trigger temperature rise that attributes to significant abrasion, diffusion and/or oxidation types of tool wear mechanisms. The reduction of tool sharpness hinders the achievement of close tolerances, as there can be metallurgical damage on the workpiece superficial layer [7].

To compensate for the absence of cutting fluids or express the possibility of avoiding the use of cutting fluids, numerous studies have been undertaken. In recent years, effective cooling technologies are actively developed. In response to the increasing demands for environmental and sustainable processes, a number of researchers have been devoting their efforts to minimize or eliminate the use of coolant in metal cutting through minimum quantity lubrication (MQL), cryogenic cooling, hybrid cooling and internal cooling techniques [9–13]. Remarkable results are achieved in term of extended tool life, low cutting temperature and improved surface roughness. Korkmaz et al. [14] reported that tool life increased by 61% and surface finish improved by 30% improvement when cutting Nimonic 80A via MQL incorporated with nanoparticles. Danish et al. [10] studied the effects of cryogenic and dry cutting on temperature and surface roughness when cutting AZ31 Mg alloy. From the results obtained, it was observed that cryogenic machining produced an improvement of 56% in surface quality and lower machined surface temperature by 60%, when compared with the dry cutting condition [10].

In addition, combination of MQL and cryogenic cooling to form a hybrid cooling technique provided superior lubrication and cooling in the cutting zone, which led to a significant reduction in crater wear [15]. Instead of using liquid nitrogen in cryogenic cooling, Tapoglou et al. [16] conducted cutting trial using cryogenic cooling with carbon dioxide (CO₂) and MQL, which resulted to a prolong tool life, when compared with the cryogenic cooling alone. Fang et al. [13] proposed a high pressure cooling (HPC) tool by creating a cooling channel through flank face and it supported an extended tool life by 40% and produced good surface quality.

Despite of outstanding performance improvement with the HPC, huge consumption of coolant led to severe environmental problems.

The principle of high velocity jet was expanded by utilizing air as a cooling fluid, replacing the conventional coolant. Cold mist jet consisted of compressed cold air and water at 0 °C were mixed in a jet nozzle to produce a substantial cooling capacity. Hence, it greatly reduced temperature during the cutting of titanium alloys [17]. Encouraging approach would be through internal cooling, which included internal heat sinks, heat exchangers, vortex tubes and heat pipe [18–21]. In internal cooling approach, cooling fluids circulate in a closed loop circuit either through a cooling channel or a pipe without injecting into the cutting zone [22, 23]. For instance, Isik developed a turning tool with a cooling channel inside the cutting tool, using pure water as a cooling fluid [24]. The results established that the tool life was extended up to 12%, because of a low cutting temperature. Evidently, channel structure is fundamentally important for an internal cooling tool. Peng et al. [25] observed that a small microchannel diameter produced the highest fluid velocity that led to a lower tool temperature.

Previously, researchers have proposed internal cooling tool by creating a cooling channel in the cutting tool to reduce tool temperature from underneath of the cutting insert [24-27]. In the various designs, several cooling fluids were able to decrease the tool temperature at its back. However, Hong et al. [28] discovered that the tool back cooling was less effective than cooling at tool rake face. This is because of the apparent distance between flank and the tool rake surfaces. Thus, it was suggested that the location of cooling source has a close relationship with the cutting zone when determining the effectiveness of cooling strategy [27, 29]. Molinari et al. [30] reported a high thermal energy generation within the primary and secondary shear zones. Temperature profile depicted a hot spot at the rake face and the generated heat intensity was subjected to specific workpiece deformation. Therefore, it is important to accurately locate the cooling source near to the cutting edges to revoke the low thermal conductivity of the insert.

Besides, magnesium alloys have received a great interest recently, because of its several applications; namely, automotive, aerospace, microelectronics and most lately in bio-medical applications. The recent uses of magnesium alloys in bio-medical industries can be attributed to their superior biodegradable properties and corrosion resistance [31]. However, low melting point contributes to the burning of the chips of magnesium alloys when machining temperature exceeds 450 °C [8]. As a result, the use of cooling fluids is needed during machining of magnesium alloys for proper cutting temperature control. Nevertheless, problem occurs when water-based coolant is applied during machining of magnesium alloys, because the reaction of water to magnesium alloys produces hydrogen gas that can lead to an explosion. To minimize this risk, dry cutting is favorable in cutting magnesium alloy, but suitable cutting parameter must be properly determined to ensure cutting process is conducted below critical temperature to avoid fire hazard, especially at elevated cutting speed.

Despite of widely established studies on indirect cooling, there are limited research focusing on indirect cooling for machining lightweight alloys, especially on magnesium alloy. Most of previous studies are mainly centered on cutting titanium and nickel-based alloys [18, 24, 27]. Besides, there is still lack of study on tackling adhesion wear mechanisms, such as extreme built-up edge (BUE) and built-up layer (BUL) during machining process by using indirect cooling. Therefore, this current study introduces an innovative and sustainable technique of submerged convective cooling (SCC) by partially submerged the tool rake face in a cooling medium to reduce tool temperature via internal cooling. Computational fluid dynamics (CFD) analysis was performed to optimize SCC cooling structure. Afterwards, a prototype of SCC tool was fabricated and turning tests on AZ31 magnesium alloy were conducted to investigate into the turning performance of the tool. Performance of the SCC was evaluated based on the capability of its heat removal, effect on cutting temperature and tool wear mechanisms.

2. Experimentation: Materials and methods

2.1 Material

AZ31 magnesium alloy cylindrical rods with diameter of 30 mm were used materials in this experimental study. They were cut into a length of 100 mm. However, only a length of 50 mm was utilized for the cutting in each pass to avoid chattering. The chemical composition of the material is presented in Table 1.

Table 1 Chemical composition of the AZ31 magnesium alloy

Chemical composition (wt.%)							
Material	Mg	Al	Zn	Mn	Si	Fe	Ca
AZ31	Bal	3.1	0.73	0.25	0.02	0.005	0.0014

2.2. SCC tool

Fig. 1 presents a SCC tool, which is considered as one of indirect cooling technique for cutting tool during machining. According to Hong et al. [28], cooling at the rake face has a profound influence for temperature reduction, instead of cooling the tool back. Therefore, in the design of SCC tool, the fluid enters the cooling module from the top of rake face and passes through the rake face before leaving via the outlet. Re-circulating fluid inside the cooling module dissipates heat from the cutting insert via convection principle through the rake face. At the contact interface between cooling module and rake face, silicon gasket was applied to seal the fluid from any leak and to avoid water contact with magnesium alloy. This cooling module was specially designed and fabricated by using aluminum alloy to create a partially enclosed rake face, while the remaining was used for the cutting operation, as shown in Fig. 2.



Fig. 1 (a) Assembly of SCC tool, showing the (b) circulating fluid inside the cooling module



Fig. 2 Description of effective surface on the tool rake face

The maximum temperature is generally noted to be near the cutting edge. Therefore, the cooling source must be located near to the cutting edge. There was no modification carried out on the cutting tool to ensure that the integrity of the insert structure and the tool remain intact. The SCC module was attached to an uncoated carbide insert CNMA120408, which was

mounted on a standard tool holder PCLNLK202012 from Mitsubishi. Tool holder has an entering angle of 95°, rake angle and inclination angle of -6°. The complete circuit of SCC setup is shown in Fig. 3. The cooling circuit consisted of a pump, a tank, a flow meter and a cooling module. They connected to each other by hose and fittings. Water was used as the cooling fluid, due to its efficiency, availability, suitability as well as its pronounced cooling ability. Besides, water does not require much treatment during disposal and could be used for a long time. Cooled water was stored in a tank, and it was pumped into the cooling module using a DC water pump at pumping rate of 1.0 L/min.



2.3 Design of internal structure of cooling module

The unique component of the SCC tool was the assembly of the cooling module. It consisted of a clamper, a fixing screw, a cooling module, an inlet and an outlet barb fitting. A clamper was used to press the cooling module tightly and securely on the insert rake face. Fixing screw was used to ensure that the cooling module was firmly attached to the cutting insert. On top of the cooling module, inlet barb was fitted by a screw thread, while a cavity was milled to accommodate the incoming cooling fluid inside the cooling module. At the back, outlet barb was also fitted by screw thread. To avoid cooling fluid leakage, a groove was created to fit a silicon gasket around the cavity area. The narrow space of the turned/machined area constrained the overall dimension of cooling structure. This condition affected the height, H of cooling module as well as the cavity depth, d, as shown in Fig. 4. The height was fixed at 16 mm, because it was the maximum allowable height before it interfered with the workpiece being machined. The cavity depth, d was set as 5 mm, taking the possibility of fluid leakage into consideration. Prior to the simulation, inlet/outlet diameter ranges were decided, based on working condition of the entire SCC tool system. As SCC tool system was designed to operate safely at designated flow rate, diameter range was determined to be around 3 - 7 mm. Consideration was taken to avoid a very low inlet diameter that could lead to over pressurized fitting and consequently a fluid leakage.



Fig. 4 (a) Cooling module (b) Section view C-C

2.4 Cutting trials

Cutting experiment was conducted using a CNC Turning T6 Compact Quicktech, considering both dry and SCC conditions, as shown in Fig. 5. The following machining parameters were kept constant: cutting speed (V_c), depth of cut (a_p) and feed rate (f) at 120 m/min, 1.0 mm and 0.1 mm/rev, respectively. Also, flow rates of the coolant or water were varied, as: 50, 90 and 130 mL/min. Cooled water with constant temperature at 20 °C was stored in the tank to act as a cooling fluid. Rake face temperature distribution was recorded for each cutting condition. Summarily, Table 2 presents the experimental details used in this study.



Fig. 5 (a) Schematic illustration of the test center and (b) the actual experimental set-up

Tab	ole	2	Ex	peri	mei	ntal	det	ails	5
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Machine	CNC Turning T6 Compact Quicktech			
Workpiece	AZ31 Magnesium alloy			
Cutting conditions	Dry			
	SCC			
	Water temperature	20 °C		
	Flow rate	50, 90 and 130 mL/min		
Cutting parameters	Cutting speed (V_c)	120 m/min		
	Depth of cut (a_p)	1.0 mm		
	Feed rate (f)	0.1 mm/rev		
Cutting tool	Tool holder	PCLNLK202012		
	Insert	CNMA120408		
Thermal camera FLIR T440				
	Camera focus distance	0.4 m		

2.5 Temperature measurement

A thermal imaging camera, FLIR T440, was utilized to locate the hot spot and temperature distribution on the rake face and chip. The FLIR tool software was installed in the computer to dynamically display the infrared images. The camera has spectral range of 7.5 to 13 μ m, a frame rate of 60 Hz and thermal sensitivity of 0.045 °C at 30 °C with 320 x 240 pixels thermal resolution to provide a total of 76,800 pixels. Emissivity value is a critical parameter in operating thermal camera. A linear relationship between thermocouple measurement and the thermal camera on AZ31 magnesium alloy was obtained with emissivity set to 0.18 [10, 34–36]. Constant emissivity of 0.18 was used to measure temperature both in dry and cryogenic

cutting conditions. It recorded a minimum temperature in a cryogenic cutting condition, which was not lower than 40 °C [10, 34], therefore emissivity value of 0.18 was similarly suitable for SCC. In this study, calibration of the thermal camera was performed by heating AZ31 magnesium alloy on hot plate from room temperature up to 300 °C, as adopted from previous studies [10, 34]. The measurement was taken at the same spot. Readings from K-type thermocouple and thermal camera were plotted in Fig. 6. Linear relationship was gained both from thermocouple and thermal camera as follows Eq. (1):



$$T_T = 1.0433T_{TC} - 9.8794 \tag{1}$$

Fig. 6 Linear relationship of temperature readings between FLIR T440 and thermocouple

To ensure consistency in capturing thermal image, the thermal camera was mounted on a camera tripod, and it was fixed perpendicular to the spindle rotational axis, as previously shown in Fig. 5. With this configuration, camera focus distance was kept to 0.4 m, which was a minimum distance recommended by manufacturer. Furthermore, effect of atmospheric attenuation was reduced at a low distance to the source, thus provided the highest resolution of measured surface [37]. The emissivity of uncoated carbide insert was determined at 0.7 by heating it to 400 °C.

2.6 Wear, tool-chip contact length and surface roughness measurements

Wear and element analyses on the magnesium alloy material and tool were carried out using a scanning electron microscopy (SEM) JEOL JSM-6010LV and energy dispersive spectroscopy (EDS) after 30 minutes of cutting, respectively. Subsequently, surface roughness was determined at four locations on every sample and average reading was taken as an arithmetic average, R_a using surface roughness Mitutoyo SJ-410 tester. The test was conducted according to ISO 4287 standard. The tool-chip contact length was observed and measured by Xoptron X80 series of high-power optical microscopy. It was identified by using the contact tracks left by the chip on the tool rake face.

3. CFD Simulation: Numerical analysis of SCC tool thermal performance

Prior to experimental work, optimum dimension of inlet/outlet diameter with varying flow rate was determined based on the maximum tool temperature. The optimization of the diameter was facilitated via ANSYS Fluent, a commercially available CFD software. The software package was applied to resolve the thermal model of the SCC tool. CFD analysis is actively utilized in engineering application, including metal cutting field [13, 25]. Table 3 depicts the material properties used in the CFD simulation.

Parameters	Insert	Cooling Module	Water	Air
		(Aluminum alloy)		
Density (kg/m ³)	15000	2719	1000	
Thermal conductivity (W/m.K)	46	202	0.6	
Specific heat capacity (J/kg.K)	203	871	4200	
Water temperature (°C)			20	
Viscosity of water (kg/m.s)			0.001	
Flow rate (mL/min)			50,90,130	

Table 3 Material properties for CFD simulation [32, 33]

Heat transfer coefficient (W/m ² .K)	 	 5
Air temperature (°C)	 	 27

Three-dimensional CFD model was developed to assess cooling capacity of the SCC tool based on the inlet/outlet diameter of the cooling module. Simulation of flow field was employed to examine the effect of inlet/outlet diameter of SCC tool on the velocity and the cooling fluid convective heat transfer coefficient, as depicted in Fig. 7. The following boundary conditions of the model were specified: (1) luid inlet was defined as mass flow inlet, (2) pressure and temperature were set to an atmospheric pressure and 27 °C respectively, for the fluid outlet. Rest of SCC tool surfaces were set to expose to the surrounding air, except cooling area, A_c and tool-chip contact area, A_{tc} .



Fig. 7 Fluid domain and heat boundary in SCC tool

In conducting the simulation, a full factorial test was implemented for independent variables of inlet/outlet diameter and flow rate, as presented in Table 4. Fluid flow inside the cooling module induced a forced convection from the motion of the fluid to absorb heat from cutting tool. The amount of heat flowing to the cooling fluid and the heat dissipation from the Newton law of cooling can be calculated based on Eqs (2) and (3), respectively:

$$\dot{Q} = \dot{m}c_p(T_{out} - T_{in}) \tag{2}$$

$$\dot{Q} = h A_c (T_s - T_f) \tag{3}$$

where \dot{m} , c_p , T_{out} , and T_{in} are mass flow rate, specific heat capacity of fluid, outlet and inlet temperatures, and *h* represents convective heat transfer coefficient, A_c denotes cooling area, T_s stands for the insert temperature and T_f is the mean fluid temperature. Before commencing the CFD analysis, the heat flux generated at tool-chip contact area was determined based on experimental tool temperature. Once the heat flux has been finalized, a parametric study on the inlet/outlet diameter was carried out, using the CFD analysis to determine optimum geometry of the final design configuration of the cooling module. Laminar model was adopted to simulate the flow field inside the cooling module. The flow rate employed in this study was determined to be a laminar flow states based on Reynolds number, *Re*, as given by Eq. (4):

$$Re = \frac{\rho VD}{\mu} \tag{4}$$

where ρ , *V*, *D* and μ are the density, inlet velocity, inlet diameter and dynamic viscosity, respectively.

Table 4 Simulation parameters

Parameter	Value
Inlet/Outlet diameter (mm)	3, 4, 5, 6, 7
Flow rate (mL/min)	50, 90, 130

4 Results and discussion

4.1 Simulation results

4.1.1 Tool-chip contact area and heat flux

Initially, dry cutting was conducted to determine the heat flux and tool-chip contact area for input parameters of the simulation. Based on dry cutting experiment, the maximum tool temperature and tool-chip contact area, A_{tc} ($L_c \ge a_p$) were determined to be 86.3 °C and (0.4 mm x 1.0 mm), respectively. An arbitrary value of heat flux was applied to the tool-chip contact area in the numerical model. Subsequently, iteration steps were taken as a procedure to attain the absolute accurate value of the heat flux, which was 2.1 $\ge 10^6 \text{ W/m}^2$. The result was validated with the experimental data based on the maximum tool temperature, as shown in Fig. 8.



Fig. 8 Comparison of maximum tool temperature in dry cutting for experimental and CFD simulation approaches

4.1.2 Effect of inlet/outlet diameter and flow rate

Maximum tool temperatures in the SCC tool are shown in Fig. 9. In general, tool temperature was proportionally increased with the inlet/outlet diameter. Lowest tool temperatures were

obtained with the inlet/outlet diameter of 3 mm for each respective flow rate. Most importantly, variation in the tool temperature was marginal, as the diameter changed from 3 to 7 mm. For instance, the tool temperature declined by only 0.5 °C for the flow rate of 50 mL/min. On the other hand, the tool temperature recorded a downward trend as the flow rate changed from 50 to 130 mL/min.



Fig. 9 Maximum tool temperature in the SCC tool

Temperature gradient of the cutting tool is shown in Fig. 10, which depicts the cooling effect from the cooling fluid or fluid flow. It was apparent that the highest temperature concentrated at tool tip, whereas the rest of the tool surfaces maintained a room temperature gradient.



Fig. 10 Temperature contour of SCC tool ($\emptyset = 3 \text{ mm}, \dot{m} = 130 \text{ mL/min}$)

Maximum tool temperature was significantly influenced by the heat transfer coefficient of the cooling fluid, as illustrated in Fig. 11. Heat transfer coefficient of cooling fluid was extracted from location cooling area, A_c of the simulation. High heat transfer coefficient implies greater high dissipation from the cutting tool. It was evident that the highest heat transfer coefficient was produced by the inlet/outlet diameter of 3 mm for each respective flow rate, and it declined gradually with the increasing inlet/outlet diameter.



Fig. 11 Heat transfer coefficient of cooling fluid

According to Cengel [38], fluid velocity greatly influences the convective heat transfer coefficient in forced convection. With this respect, the effects of inlet/outlet diameter on fluid velocity and the percentage reduction of fluid velocity for respective diameters and flow rates are depicted in Fig. 12. The highest fluid velocity was recorded when the inlet/outlet diameter was 3 mm for each set of flow rate, and it continued to drop with increased inlet/outlet diameter. Therefore, the highest heat transfer coefficient can be attributed to the inlet diameter of 3 mm, as illustrated in Fig. 11.

Besides, the reduction of fluid velocity was analyzed, as shown in Fig.12. This is a vital indicator to ensure that the fluid velocity remains at its highest velocity. From Fig. 12, regardless of the fluid flows, the loss of fluid velocity persisted as the inlet/outlet diameter increased. An inlet/ outlet diameter of 3 mm recorded the least loss of velocity for each set of flow rate with the minimum loss of 15% for a flow rate of 130 mL/min. Based on the simulation results, it can be concluded that effective convective heat transfer coefficient can lead to a low tool temperature. The highest heat transfer coefficient was obtained when the inlet/outlet diameter was 3 mm, and it maintained an upward trend with the flow rate. Considering inlet velocity and tool temperature, SCC tool exhibited a pronounced cooling performance when the inlet/outlet diameter was 3 mm. Thus, the optimum dimension of inlet/outlet diameter was confirmed, and the actual fabricated SCC tool is shown in Fig. 13.



Fig. 12 Influence of inlet/outlet diameter on reduction of fluid velocity at flow rates of (a) 50, (b) 90 and (c) 130 mL/min



Fig. 13 Actual SCC tool

4.2 Heat distribution on rake face

Thermal imaging aided the identification of the hot spot and analysis of the heat distribution on the rake face, when exposed to heat generated from cutting process. Thermal camera was utilized to visualize concentration of heat spread on the tool rake face. Thermal image at rake face was captured immediately at end stroke of cutting. To avoid interruption from the chip and workpiece, the tool was retracted from the workpiece prior to capturing the image. As shown in Fig. 14, there was a significance drop in tool temperature, but a nearly similar chip temperature of AZ31 magnesium alloy was obtained. Fig. 15 shows thermal distribution on the rake face after 1.0 minute of cutting for both dry and SCC conditions. There was a significant reduction on the tool rake face temperature from dry to SCC condition at 130 mL/min; precisely from 86.3 to 42.1 °C, as shown in Figs 15(a) and (d), respectively.



Flow rate (ml/min)

Fig. 14 Tool and chip temperatures at different flow rates of water



Fig. 15 Thermal images of heat distribution and maximum tool temperatures after disengagement from the workpiece, under: (a) dry, SCC conditions at flow rates of (b) 50, (c) 90 and (d) 130 mL/min

This reduction or improvement was roughly 50%, while internal cooling tool with a tool back cooling developed by Isik [24] reduced tool temperature approximately by 26%, when compared with the dry cutting condition. On the other hand, green closed internal cooling tool also applied tool back cooling and was able to reduce tool temperature by 87.1 °C, which was equivalent to 60%, when compared with a tool without internal cooling, but the inlet water temperature and ambient was 12 °C [23]. Evidently, the effect of flow rate in SCC condition showed a downtrend in tool temperature, yet the difference was minor and between 1 to ~5 °C, as captured and presented in Figs 15(b)-(d). Low thermal conductivity of uncoated tungsten carbide might have hindered the heat transfer from the tool to the cooling fluid, even though the flow rate was raised. Minton et al. [27] had discovered that the uncoated tool conducted heat slower than diamond coated tool when cutting titanium alloy with internal cooling system, due to low thermal conductivity.

Also, it was observed in a dry condition that the heat distribution was spreading all over the rake face as well as to the cutting tool. However, the highest temperature was spotted slightly away from the cutting edge; the area where the chip had contact with the tool. In contrast, for SCC condition, the heat was maintained near the tool tip without heating up the entire tool, with a less peak temperature generated. Since a lower feed rate was employed in this study, the contribution of heat at the rake face was mainly originated from the sliding chip [39]. Therefore, it was understood that the heat source was moving towards the cooling source for SCC condition. Besides, it has been established in cutting simulation that maximum temperature occurred at 0.4 mm away from the cutting edge and the heat flux flowed into the tool along the entire contact region [40]. Consequently, tool temperature was reduced in SCC condition. This was in agreement with the investigation conducted by Minton et al. [27] and Wu et al. [23]. They reported that internally cooled tool significantly exhibited a reduction in its temperature.

In metal cutting, 70 to ~ 80% of heat generated is carried away by the chip. Fig. 16 shows the temperature variation of chip for different machining conditions. Dry condition produced chip temperature of 248.3 °C, whereas lowest chip temperature of 230 °C was recorded with SCC condition at a flow rate of 130 mL/min. This decrease or enhancement was approximately 8%. The variation of chip temperatures between dry and SCC conditions was not much or smaller, when compared with that of tool temperature. This phenomenon did not imply ineffectiveness of submerged cooling, instead it was a consequence of enormous heat reduction in the tool. This was evidently demonstrated by Ozel [41], in which the reduction of 180 °C at tool-chip interface temperature led to 30 °C decrease in chip temperature. Besides, the observed low deviation of the chip temperatures established the fact that frictional heat was evacuated by the chip, instead of being conducted by the tool. This phenomenon can be linked to high chip velocity [42].



Fig. 16 Thermal image at maximum chip temperature of AZ31 magnesium alloy during (a) dry as well as SCC conditions at flow rates of (b) 50, (c) 90 and (d) 130 mL/min

4.3 Contact length, chip formation and tool wear mechanisms

Effects of cutting conditions and flow rates on tool-chip contact length were investigated and discussed in this sub-section. As shown in Fig. 17, higher value of tool-chip contact length of 0.415 mm was recorded in dry condition when compared with SCC with an average value of 0.300 mm, resulting to nearly 28% reduction. This occurrence can be related to that of tool and chip temperatures, as previously explained. Long contact length implied larger contact area and high stress between the chip and the tool. Thus, enormous amount of heat generated at tool-chip interface caused by the friction was absorbed by the tool [43].



Fig. 17 Tool-chip contact lengths at different flow rates

Considering Fig. 18, chip produced in dry condition was continuous type, which was coincidental to tool temperature and contact length. Nevertheless, in the SCC system/condition,

a downtrend in tool-chip contact length was observed. With higher flow rate, the tool-chip contact length was reduced. This was an indication that the cooling had a significant effect on the tool-chip contact length. At lowest flow rate of 50 mL/min, contact length was 0.33 mm, while maximum flow rate of 130 mL/min reduced contact length to 0.25 mm. Tasdelen et al. [44] reported a similar outcome in which MQL and compressed air recorded a comparable total contact length, due to chip-up curling caused by the cooling effect.



Fig. 18 Chip formation and tool-chip contact length for different flow rates.

High flow rate provided more heat absorption, which was evidently shown by tool and chip temperatures (Fig. 14). The low tool-chip contact length produced discontinuous and shorter chips, as depicted in Fig. 18. Besides, the structure of the cooling module incorporated on the rake face indirectly contributed to the low contact length. The structure of SCC system created an obstruction to the chip, which forced the chip to curl up similar to that of cutting tool with chip breaker.

Furthermore, BUL is commonly observed during machining of Mg alloy [45, 46]. BUL is a kind of adhesion wear mechanism in metal cutting that is thermally sensitive, especially to workpiece-tool temperature [47]. This frequent wear mechanism occurs always at high temperature and is very difficult to prevent [48]. The zone where heat is absorbed either by the cutting edge or flank face is an identified favorable location of BUL formation. The phenomenon of BUL during cutting of magnesium alloy is associated to low melting temperature of around 618 °C, thus the material tends to weld on the tool rake face. Presence of both manganese (Mn) and aluminum (Al) compounds in the BUL area has been identified as the key factors responsible for adhesion mechanism in cutting Mg alloy, as it has high affinity with tool materials [45].

Moving forward, the results from the chemical analysis conducted using EDS are shown in Fig. 19. It was evidently observed in both conditions that there were presence of Mn and Al elements on the rake face. In this current study, both BUE and BUL were observed in both dry and SCC cutting conditions. However, the severity of BUE and BUL were different. With dry condition, both BUE and BUL produced were worse. But, the severity of these wear mechanisms improved or decreased tremendously with SCC condition. SEM image in Fig. 20 shows BUE at the cutting edge and BUL on the rake face. They were intensified in dry condition, due to the higher cutting temperature. It can be further explained that the plastic deformation of the workpiece material in primary zone generated enormous heat closed to the

cutting edge, therefore it caused melted AZ31 magnesium alloy to adhere on the cutting edge. The significant formation of BUL observed on the tool rake face in dry condition can be attributed to the rapid heat growth, due to the friction effect between the chip produced and the tool.



Fig. 19 EDS spectra on tool flank faces during (a) dry cutting and (b) SCC at flow rate of 130

mL/min



(a) Dry cutting.



(b) SCC at 50 mL/min.





(c) SCC at 90 mL/min.



(d) SCC at 130 mL/min.

Fig. 20 Formation of BUE and BUL on tool rake faces during (a) dry condition and (b)-(d) different SCC flow rates On the other hand, cutting with SCC provided a cooling effect on the tool. With the presence of cooling effect, cutting process occurred below the critical temperature. Hence, the melting temperature of AZ31 magnesium alloy was delayed at the cutting edge. However, friction between the chip and tool raised the temperature rapidly as the chip flowed on the rake face. This led to workpiece material adhesion on the tool rake face, but it was immensely improved in SCC condition with clean surface observed on the tool face, as shown in Fig. 20.

Surface roughness possesses great influence on the final quality of workpiece material. In case of AZ31 magnesium alloy, smoothen surface roughness can improve its corrosion resistance [49]. From Fig. 21, surface roughness was improved under SCC condition when compared with dry condition. Surface roughness in SCC decreased or improved by nearly 37% in comparison with dry cutting. Similar phenomenon was observed with the internal cooling tool studied by Isik, whereby surface roughness achieved a better quality up to 13% than dry machining when turning nickel-based superalloys [24]. A better surface roughness in SCC can be mainly attributed to the reduction in temperature at cutting zone, thus decreasing the melting of AZ31 magnesium alloy on machined surface and cutting edge. This was similarly reported on cryogenic cutting of magnesium alloy, where surface roughness was improved due to cooling effect [10]. Nevertheless, cryogenic cooling outperformed the SCC by improving the surface roughness by 56%, due to extreme cooling obtained from liquid nitrogen. Evidently, cutting magnesium alloy with MQL remarkably improved the surface roughness by 53%, owing to the cooling and lubrication effects [50]. However, there was no improvement in the surface roughness using SCC with increasing flow rate, and it maintained value of around 0.151 μm. Surface roughness eventually deteriorated to 0.178 μm with SCC at maximum feed rate of 130 mL/min, due to the irregular flow of chips and consequence of uneven BUE formation along the cutting edge.



Fig. 21 Surface roughness of AZ31 magnesium alloy under at different flow rates

5 Conclusions

In this study, innovative and sustainable cooling technique via submerged convective cooling was introduced. The technique proposed an environmentally friendly machining strategy, using water as a coolant and other suppressed mineral-based fluids. The effects of using the technique were investigated and analyzed on both tool and chip/workpiece. Dry turning machining/cutting was conducted and compared with the effectiveness of SCC condition with respect to tool wear, temperature, chip contact length and surface finish of AZ31 magnesium alloy material. Based on experimental results obtained, the following concluding remarks can be drawn:

• CFD simulation revealed that small inlet/outlet diameter of 3 mm significantly contributed to tool temperature reduction, because of the effective heat transfer coefficient of the SCC.

- SCC condition significantly reduced tool and chip temperatures by around 50% and 8% respectively, when compared with the dry cutting condition. Slight variation was obtained at both maximum tool and chip temperatures with an increasing flow rate in SCC.
- Tool-chip contact length obtained with SCC reduced by approximately 28% when compared with the dry cutting condition, implying consequence of cooling effect from the sustainable cooling fluid. High flow rate produced less tool and chip contact lengths, which consequently led to a low cutting tool temperature.
- Both BUE and BUL were observed in SCC and dry cutting conditions. However, severity
 of both turning-induced damage responses profoundly improved or reduced in SCC
 condition, due to delay in melting of AZ31 magnesium alloy. This was significantly
 attributed to the presence of cooling fluid from SCC condition.
- Finally, as BUE and BUL were reduced in SCC, surface finish of AZ31 magnesium alloy
 was decreased by nearly 37%, when compared with dry cutting condition. This was a
 notable improvement, as some performance properties and fracture of many components
 depend on their surface roughness values.

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Declarations

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