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Steam as coolant and lubricant in turning of metal matrix composites

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Abstract: Green cutting has become focus of attention in ecological and environmental protection. Steam is cheap, pollution-free and eco-friendly, and then is a good and economical coolant and lubricant. Steam generator and steam feeding system were developed to generate and feed steam. Comparative experiments were carried out in cutting AA6061-15 vol.% SiC (25 μm particle size), with cubic boron nitride (CBN) insert KB-90 grade under the conditions of compressed air, oil water emulsion, steam as coolant and lubricant, and dry cutting, respectively. The experimental results show that, with steam as coolant and lubricant, gradual reduction in the cutting force, friction coefficient, surface roughness and cutting temperature values were observed. Further, there was reduction in built up edge formation. It is proved that use of water steam as coolant and lubricant is environmentally friendly.

Key words: Metal matrix composites (MMCs), Turning, Cutting force, Thrust force, Friction coefficient, Surface roughness, Built-up edge (BUE)

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INTRODUCTION

The benefit of using composite materials and the cause of their increasing adoption is to be looked for in the advantage of attaining property combinations that can result in a number of service benefits. Among these are: increased strength, decreased weight, higher service temperature, improved wear resistance and higher elastic module.

Cutting fluid is usually used to reduce cutting force, lower cutting temperature, prolong tool life and enhance machining efficiency and surface finish quality during machining. In general, the better the performance of cutting fluid, the more pollutant it is to environment. In the 21st century, with environment protection awareness enhanced and laws and regulations enforced, green cutting has become a general trend in machining (Chen, 1984).

In the 1990s, Podgorkvv *et al.*(1992) and Godelvski *et al.*(1998) proposed a new and pollution-free green cutting technique with water vapor as coolant and lubricant during cutting process. Further fluid jet assisted machining as a highly effective method for cutting of conventional materials has been well explored (Li and Seah, 2001; Li, 1996a; 1996b; Kaminski and Alvelid, 2000; Hung *et al.*, 1997; Weinert, 1993; Wang and Rajurkar, 1997; Mazurkiewicz *et al.*, 1989; Shetty *et al.*, 2006a; 2006b; 2006c; 2007a; 2007b; Shenoy *et al.*, 2006), in which fluids, such as air, water or steam, mainly act as transportation carriers carrying the heat away from the cutting region, and the efficiency of such a cooling method largely depends on the jet pressure and flow rate. The results show that the cutting force is reduced, the friction coefficient and the surface roughness value R_a are decreased, and the cutting temperature is lowered. The objective of this study is to develop an environmental friendly lubricant based upon a new concept of having a high lubricity despite of penetration of steam. In this paper, some experiments are done based on steam as coolant and lubricant. The experimental results indicate that the new method can be applied to industry for improving operation environment and lowering cost.

EXPERIMENT

Steam generator and steam feeding system

The steam generator and steam feeding system are developed in which jet flow parameters (pressure, flow rate) and cooling distance (it is the distance between nozzle and cutting zone) are controllable. Figs.1a and 1b show the top view and front view of steam generator and steam feeding system, respectively.

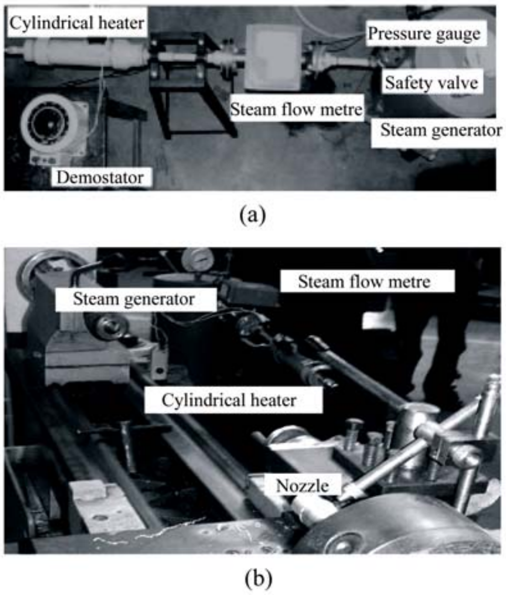

Fig.1 Steam generator and steam feeding system. (a) Top view; (b) Front view

Simulation of distribution of velocity

The main part of the experimental setup consists of a saturated steam supply, a super heater, a servo valve and a pressure gauge for controlling the supply pressure, a 2 mm exit diameter nozzle with a steam flow meter for steam flow rate measurements. The steam jet investigated discharges into the rake face as a one-component, i.e., single-phase fluid. However, the flow goes through a phase-change and mixes with air as another one-component, hence, it has different constituents at different locations (e.g., just steam in the core region). Mass fractions of the components of the jet vary throughout the jet. In the present simulations, the steam jet and necessary boundary conditions were chosen in a simplified form. It was assumed that the steam leaving the nozzle was wet with inlet boundary conditions calculated from wet-equilibrium expansion. Phase changes were ignored in mixing the wet steam with the surrounding air. Hence, the theoretical approach taken to solve the steam jet flow was based upon the assumption that the steam-droplet-air mixture is locally homogeneous.

The velocity of steam jet flow directly influences lubricating and cooling effect. Through measuring velocity of nozzle in different locations in the cooling distance, the distribution of velocity is modeled in ANSYS with different colors standing for different values of velocity. Figs.2a and 2b show velocity and vector plot of the simulated results, respectively.

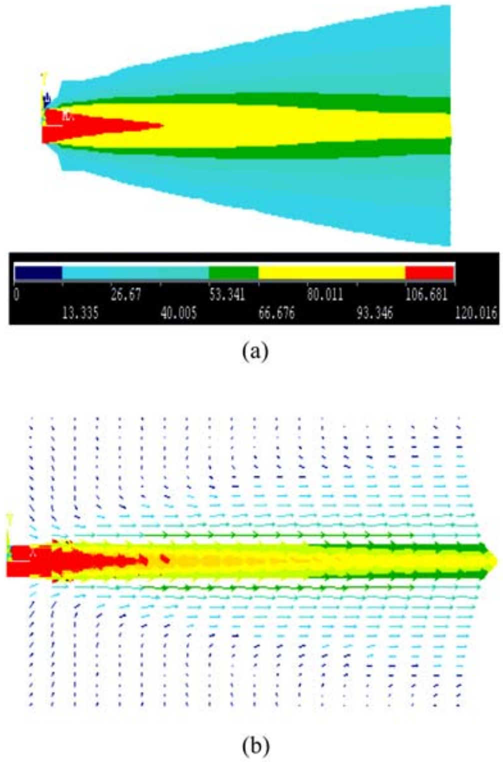

Fig.2 (a) Velocity and (b) vector plot of the simulated results

Cutting experiments

The selected experimental material was manufactured by stir casting process. The matrix materials used was 99.9% pure aluminum, and 15 vol.% SiC particles with an average size of 25 μm were applied as the reinforcement element. The specimens were in bar shapes of 40 mm diameter and 120 mm length. The chemical composition of specimens was given in Table 1. Turning method as machining process was selected. The experimental study carried out in PSG A141 lathe (2.2 kW). The selected cutting tool was cubic boron nitride (CBN) insert KB-90 (ISO code), for machining of metal matrix composite (MMC) materials. The ISO codes of cutting tool insert and tool holder were shown in Table 2. The selected machining parameters were given in Table 3. The machining process is conducted as dry, oil water emulsions, compressed air and steam cutting, and completed after 80 s turning period. The cutting force and thrust force were measured respectively by using an IEICOS Digital tool dynamometer shown in Fig.3. Surface roughness was measured using Taylor/Hobson surtronic 3+ surface roughness measuring instrument. Examination of built-up edge and surface roughness was observed in JEOL JSM-6380LA Analytical scanning electron microscope (SEM).

EXPERIMENTAL RESULTS AND DISCUSSION

In this paper, to compare the effects of steam, oil water emulsions, compressed air and dry cutting were devoted. The cutting forces, thrust forces and surface roughness values were obtained, friction coefficients on the rake face of tool were investigated and built-up edge formation was observed. Each investigated subject was devoted to different headings as given below.

Table 1 Nominal chemical composition of base metal (6061 Al alloy)

Element	Weight percentage (%)
Cu	0.25
Mg	1
Si	0.6
Cr	0.25
Al	Balance

Table 2 Details of cutting tool and tooling system

Type	Specification
Tool holder	STGCR 2020 K-16; CTGPR 1212 F-11
Tool geometry	Approach angle: 91°; Tool nose radius: 0.4 mm; Rake angle: 0°; Clearance angle: 7°
CBN tool insert (KB- 90)	TPGN 160304-LS; TPGN 110304-LS

Table 3 Machining condition

Parameter	Description
Condition of machining	Turning
Machine tool used	PSG A141 lathe (2.2 kW)
Cutting speed (m/min)	150
Feed (mm/r)	0.2
Depth of cut (mm)	0.5, 1.0, 1.5, 2.0
Coolant used	Steam, oil water emulsions, compressed air, dry cutting
Coolant pressure (bar)	7
Cooling distance (mm)	30

Cutting force (P_c)

It can be seen from Fig.4, when steam as coolant and lubricant, the main cutting force is reduced, respectively, about 25%~35%, 15%~25% and 5%~10% by comparing with dry cutting, oil water emulsion and compressed air. Because steam forms high velocity jet flow by the nozzle and in the cutting zone, it will fill up the capillaries of tool-chip interface in gaseous state and high temperature steam will form boundary lubrication layer of high adsorption strength. As a result, the main cutting force is remarkably reduced.

Thrust force (P_t)

The thrust forces of steam, oil water emulsions, compressed air, and dry cutting were illustrated for

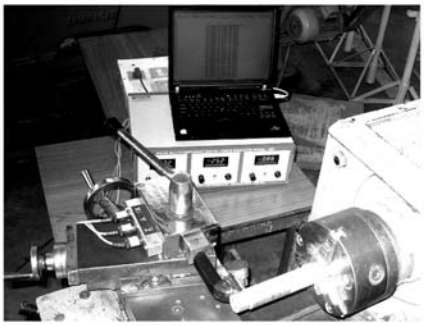

Fig.3 Force measurement layout

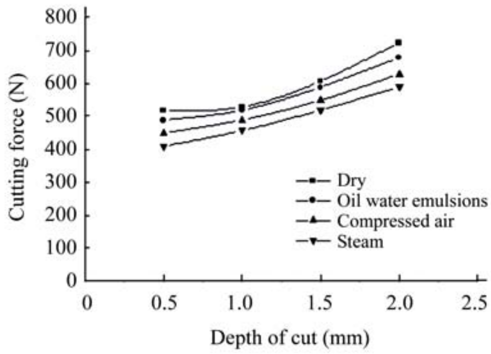

Fig.4 Cutting force comparison

different depths of cut in Fig.5. It was observed that the minimum thrust force was obtained by steam application. Oil water emulsions produced higher thrust forces and the dry cutting gave maximum value.

Friction coefficient (*μ*)

The friction coefficient on rake face of tool can be calculated by using measured values (P_c, P_t) and Merchant's theory (Chen, 1984) as

$$\mu = \frac{P_t \cos\gamma + P_c \sin\gamma}{P_c \cos\gamma + P_t \sin\gamma}, \quad (1)$$

where μ is the coefficient of friction, P_c the cutting force, P_t the thrust force and γ the rake angle. The cutting force and thrust force were measured by dynamometer. Fig.6 shows that the lowest friction coefficient was captured by steam. As steam accesses the cutting zone with high velocity jet flow and forms much steadier boundary lubrication layer, it eliminates all or part adhesion of tool-chip fresh surface, alleviates seizure phenomena and accelerates sub-layer plastic flow. Hence the friction coefficient is decreased effectively.

Cutting temperature

The cutting temperature was measured using thermocouple and it was found to increase with an increase in the depth of cut. In general, the cutting fluid mainly depends on heat convection to reduce the cutting temperature. Steam can reduce the contact friction of tool-chip interface with high efficiency lubricating action, and then has indirectly cooling effect. Steam temperature is much lower than the cutting temperature, so steam has some function of heat convection. Under the conditions of double functions of indirect cooling and heat convection, the cutting temperature is decreased much more. As it is seen from Fig.7, when steam is used as coolant and lubricant, the cutting temperature reduced to about 20%, 30%, 40%, compared with the other conditions of dry cutting, compressed air and oil water emulsion.

Surface roughness

From Fig.8 it can be seen that under steam lubrication conditions the surface roughness values also dropped down significantly.

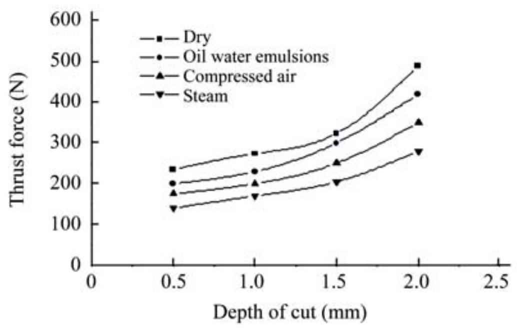

Fig.5 Thrust force comparison

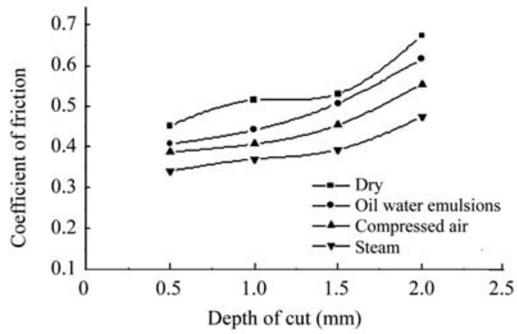

Fig.6 Coefficient of friction comparison

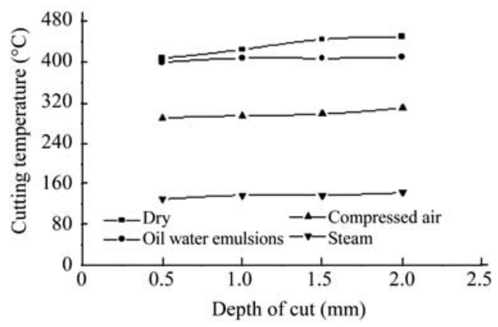

Fig.7 Cutting temperature comparison

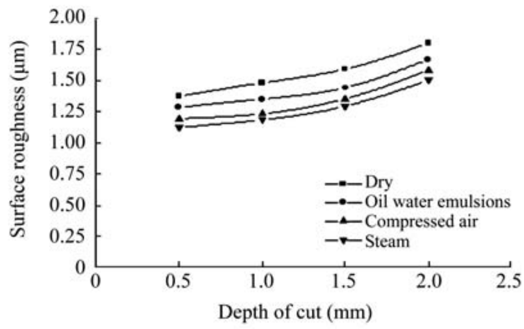

Fig.8 Surface roughness value R_a

Fig.9 shows the SEM images of surface roughness on Al-SiC at 2 mm of cut under dry cutting, oil water emulsions, compressed air and steam cutting.

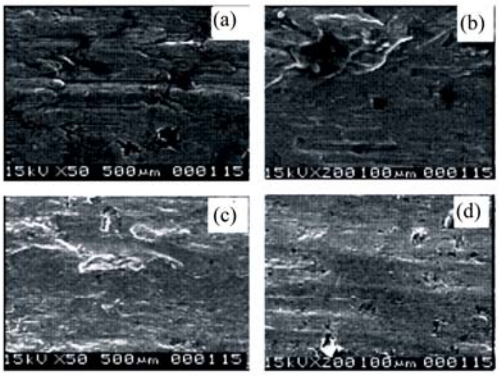

Fig.9 SEM images showing the surface roughness on Al-SiC at 2 mm depth of cut. (a) Dry cutting; (b) Oil water emulsions; (c) Compressed air; (d) Steam cutting

Comparison of chips forms

The form of chip produced is one of the major parameters influencing productivity in metal cutting industry. Generally, there are two groups of chip forms: acceptable chips and unacceptable chips, for convenience of handling. Acceptable chips do not interfere with the work or machine tool and cause no problems of disposal. Unacceptable chips interrupt regular manufacturing operation, as they tend to entangle the tool and work piece and safety problems to operators. Entangling chips can harm the surface finish and even lead to unexpected tool failure.

Chips formed during the machining (turning) of 6061 Aluminium 15 vol.% SiCp composites in steam cutting under different cutting conditions for different depth of cut are shown in Fig.10. It is clear that the chip shapes formed during steam as coolant and lubricant in turning of Al/SiC-MMC are in the form of saw tooth with high radius curling circle and broken into small pieces.

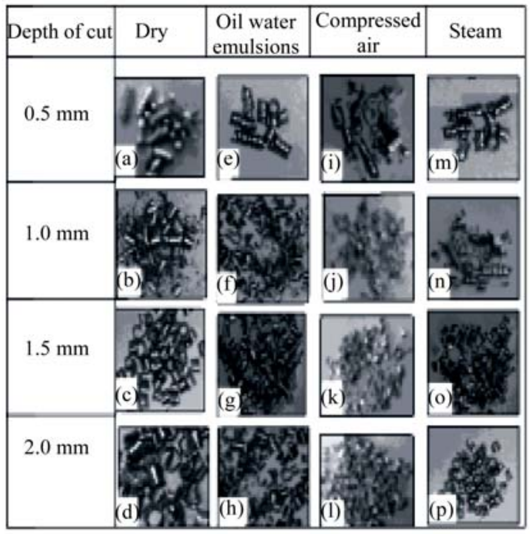

Fig.10 Comparison of chip samples under dry cutting, compressed air, oil water emulsions and steam

Built-up edge formation

Fig.11 shows the built up edge (BUE) during machining of Al-SiCp MMCs under dry, compressed air, oil water emulsions and steam as coolant at 2 mm depth of cut. The turning operations were performed considering constant 150 m/min cutting speed, 0.20 mm/r feed and for 80 s turning period. From Fig.11, it can be observed that the BUEs increase under dry condition, compressed air, oil water emulsions compared to steam as coolant.

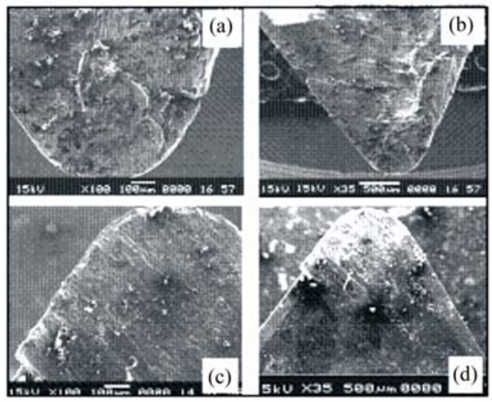

Fig.11 SEM images showing the BUEs on the cutting tools after machining Al-SiC at 2 mm depth of cut. (a) Dry cutting; (b) Oil water emulsions; (c) Compressed air; (d) Steam cutting

CONCLUSION

(1) With steam as coolant and lubricant, the cutting force is reduced respectively by about 25%~35%, 15%~25% and 5%~10% as compared with dry cutting, oil water emulsions and compressed air; the friction coefficient and the surface roughness value are decreased respectively; the cutting temperature is lowered, too.

(2) Steam as coolant and lubricant can be an

advantage in forming acceptable chips.

(3) When steam is used as coolant and lubricant, it possesses better lubricating action because of excellent penetration performance and forming of low shearing strength lubrication layer.

(4) There was gradual reduction in BUE formation with steam as coolant in turning of Al-SiC MMCs.

(5) Accordingly steam as coolant and lubricant has the advantages of being cheap, pollution-free and harmless. There is no need for disposal or recycling. It provides fundamental theory for green cutting.

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