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CUTTING TEMPERATURE, TOOL WEAR, SURFACE ROUGHNESS AND DIMENSIONAL DEVIATION IN CRYOGENIC MACHINING

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ABSTRACT

Machining of steel inherently generate high cutting temperature, which not only reduces tool life but also impairs the product quality. Conventional cutting fluids are ineffective in controlling the high cutting temperature and rapid tool wear. Further they also deteriorate the working environment and lead to general environmental pollution. Cryogenic cooling is an environment friendly clean technology for desirable control of cutting temperature. The present work deals with experimental investigation in the role of cryogenic cooling by liquid nitrogen jet on cutting temperature, tool wear, surface finish and dimensional deviation in turning of AISI 1060 steel at industrial speed-feed combination by coated carbide insert. The results have been compared with dry machining and machining with soluble oil as coolant. The results of the present work indicate substantial benefit of cryogenic cooling on tool life, surface finish and dimensional deviation. This may be attributed to mainly reduction in cutting zone temperature and favorable change in the chip-tool interaction. Further it was evident that machining with soluble oil cooling failed to provide any significant improvement in tool life, rather surface finish deteriorated.

Keywords: Turning, Cryogenic cooling, Coated carbide, Wear, Roughness and dimensional deviation.

1. INTRODUCTION

Machining is the process, in which a tool removes material from the surface of a less resistant body, through relative movement and application of force. The material removed, called chip, slides on the face of tool, known as tool rake face, submitting it to high normal and shear stresses and, moreover, to a high coefficient of friction during chip formation [1]. Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. High cutting temperature, which adversely affects tool life, dimensional and form accuracy, surface integrity of the product, inherently characterize high speed machining. In industry, Such high cutting temperature and its detrimental effects are generally reduced by (i) proper selection of process parameters (ii) proper selection and application of cutting fluid and (iii) using heat and wear resistance cutting tool materials like carbides, coated carbides and high performance ceramics. But high performance ceramics (CBN and diamond) are extremely heat and wear resistive but those are too expensive and are justified for very special work materials and requirements where other tool are not effective.

Nowadays, in high production machining coated tools are being used to a large extent [2,3]. Proper coating can provide thermal as well as diffusion barrier which are essential in machining steel [4]. Coatings also provide reduced friction between the tool and chip [5,6]. Thus the wear mechanisms of coated tools are expectedly quite different from that of uncoated ones.

Conventionally applied coolants even with extreme pressure additives fail to provide desirable control of cutting temperature, as they cannot penetrate the chip-tool interface due to predominantly plastic contact between the tool and chip especially at high cutting speed [7-9]. High-pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature [10]. However, such coolants are major source of pollution from the machining industry and its disposal cost is also increasing due to strict environmental regulations [11]. Therefore, the handling and disposal of cutting fluids must obey rigid rules of environmental protection. On the shop floor, the operators may be affected by the bad effects of cutting fluids, such as by skin and breathing problems [12].

Possibility of controlling high cutting temperature in high production machining by some alternative methods has been reported. Cutting forces and temperature were found to reduce while machining steel with tribologically modified carbide inserts [13]. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50% [14]. Application of CO_2 in the form of liquid jet also provided some reduction in cutting forces [15].

Some works have recently been done on cryogenic cooling by liquid nitrogen jet in grinding some steel of common use [16-18]. Compared to dry grinding and wet grinding with conventional fluid, cryogenically cooled grinding provided much better surface integrity, lesser cutting forces and longer wheel life, though in different degrees for different steels, mainly through reducing temperature, preventing wheel loading and retaining grits sharpness.

The earlier work [19-22] of late 60's and early 70's reported that cryogenic cooling notably reduced cutting force and temperature and improved tool life and surface integrity in continuous as well as interrupted machining. Beneficial effects of cryogenic cooling in turning stainless steel and KEVLAR composite by diamond tools were also reported [23]. The favorable role of cryogenic cooling on chip breaking, cutting temperature, cutting force and tool wear in turning [24-29] and overall performance of carbide inserts in face milling [30] has recently been reported. While investigating the tool wear mechanism in turning reaction bonded silicon nitride with CBN inserts, the tool life found to increase due to cooling by liquid nitrogen [31,32].

The review of the literature suggests that cryogenic cooling provides several benefits in machining and grinding. The main objectives of the present work is to experimentally investigate the role of cryogenic cooling by liquid nitrogen jet on tool wear, dimensional accuracy and surface finish in turning of AISI 1060 steel at industrial speed-feed condition by coated carbide insert and compare the effectiveness of cryogenic cooling vis-a-vis dry machining and under conventional cutting fluids.

2. EXPERIMENTAL INVESTIGATION

For the present experimental studies, AISI-1060 steel bar (φ125mm X 760 mm) was turned in a high power rigid lathe (Lehman Machine Company, St. Louis, USA, 15hp) by coated carbide insert at industrial speed-feed combinations under both dry, wet and cryogenic cooling conditions. The experimental conditions are given in Table-1. The ranges of the cutting velocity (V_c) and feed rate (S_o) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed.

The photographic view of the experimental setup is shown in Fig.1. For cooling and lubrication, liquid nitrogen (-196^{o}C) in the form of thin but high speed was impinged from a specially designed nozzle along the cutting edge of the insert, as indicated in Fig.1, so that the coolant reaches as close to the chip-tool and the work-tool interfaces as possible. The liquid nitrogen jet has been used mainly to target the rake surface and flank surfaces along the auxiliary cutting edge and to protect the auxiliary flank to enable better dimensional accuracy.

Table 1: Experimental conditions

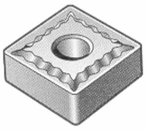
Machine tool	High power rigid lathe, USA, 15 hp
Workpiece	AISI-1060 steel
Cutting tool	Coated carbide, SNMG-120408, Drillco 
Coating	TiCN + Al_2O_3
Tool holder	PSBNR 2525M12, Drillco
Tool geometry	-6, -6, 6, 6, 15, 75, 0.8 (mm)
Process parameters	
Cutting velocity	72, 94, 139 and 164 m/min
Feed rate	0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut	1.5 mm
Environment	Dry, Wet and Cryogenic cooling

Fig 1. Photograph view of the experimental set-up

The effectiveness, efficiency and overall economy of machining any work material by given tools depend largely only on the machinability characteristics of the tool-work materials under the recommended condition. Machinability is usually judged by (i) pattern and mode of chip formation (ii) cutting temperature which affect product quality and cutting tool performance (iii) the magnitude of the cutting forces which affects power requirement and vibration (iv) tool wear and tool life and (v) surface finish and dimensional deviation. In the present work, cutting temperature, chip pattern, tool wear, surface finish and dimensional deviation are considered for studying the role of cryogenic cooling. In the present work, cutting temperature, tool wear, surface roughness and product accuracy are considered for studying the role of cryogenic cooling.

The average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration.

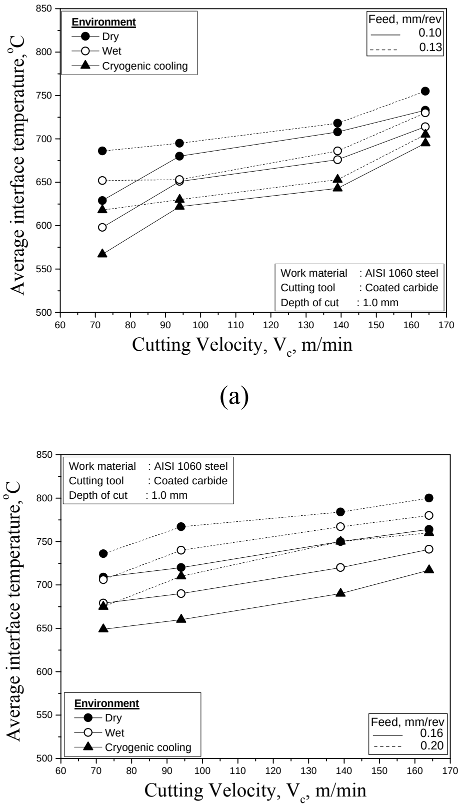
The machining was interrupted at regular intervals to study the growth of wears on main and auxiliary flanks for all the trials. The flank wears were measured using in metallurgical microscope (Carl Zesis, 351396, Germany) fitted with micrometer of least count 1 μm. The surface roughness on the job was also monitored by measuring with a contact type stylus (Surtronic 3+ roughness checker, Rank Taylor Hobson, UK). At the end of tool life, the cutting inserts were inspected under scanning electron microscope (Hitachi, S-2600N, Japan) to study the prevalent wear mechanism. The deviations in the job diameter before and after cuts were measured by a precision dial gauge, which was traveled parallel to the axis of the job.

3. EXPERIMENTAL RESULTS AND DISCUSSION

During machining any ductile materials, heat is generated at the (a) primary deformation zone due to shear and plastic deformation (b) chip-tool interface due to secondary deformation and sliding and (c) work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is maximum. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic or bulk.

However, it was observed that the liquid nitrogen jet in its present way of application enabled reduction of the average cutting temperature (θ_{avg}) by about 10 to 20% depending upon the levels of the process parameters, V_c and S_o. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices. The cutting temperature generally increases with the increase in V_c and S_o, though in different degree, due to increased energy input and it could be expected that cryogenic cooling would be more effective at higher values of V_c and S_o. But actually it had been otherwise as can be shown in Fig.2.

The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fails by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc. depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and microchipping at the sharp cutting edges.



(a)

(b)

Fig 2. Variation in interface temperature with Vc under different environments at (a) lower and (b) higher feed

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tool and work material and the machining conditions undertaken, the tool failure mode has been mostly gradual wear.

Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems. The life of carbide tools, which mostly fail by wearing, is assessed by the actual machining time after which the average value (V_B) of its principal flank wear reaches a limiting value of 0.3 mm. Therefore, attempts should be made to reduce the rate of growth of flank wear (V_B) in all possible ways without much sacrifice in MRR. Fig.3 clearly shows that average flank wear, V_B decreased substantially by cryogenic cooling. Crater wear of carbide tools in machining steels particularly at higher V_c and S_o occur by adhesion and diffusion as well as post abrasion, whereas, flank wear occurs mainly by micro-chipping and abrasion and with increase in V_c and S_o adhesion and diffusion also come into picture due to intimate contact with the work surface at elevated temperature.

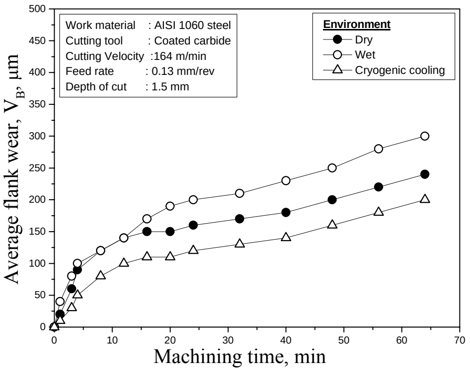


Fig 3. Growth of V_B with machining time under different environments at cutting velocity 164 m/min

The cause behind reduction in V_B observed may reasonably be attributed to substantial reduction in the cutting temperature by cryogenic cooling particularly the jet impinged along the main cutting edge, which helped in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion types of wear which are highly sensitive to temperature. Because of such reduction in rate of growth of flank wear the tool life would be much higher if cryogenic cooling is properly applied. Auxiliary flank wear (V_S), though occurs less intensively, also plays significant role in machining by aggravating dimensional inaccuracy and roughness of the finished surface. It appears from Fig.4 that auxiliary flank wear (V_S) has also decreased sizeably due to proper temperature control under cryogenic cooling.

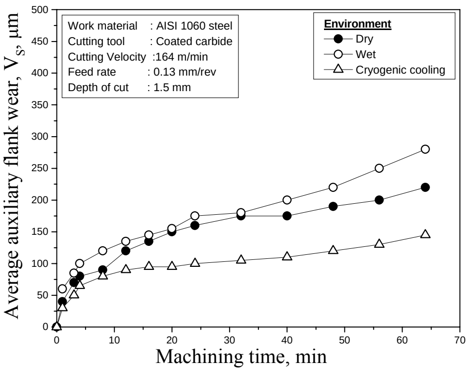


Fig 4. Growth of V_s with machining time under different environments at cutting velocity 164 m/min

The favorable effect of cryogenic cooling on flank wear of insert has been briefly shown in Fig.5. After 64 minutes of machining the insert attained around 240 µm average flank wear under dry, 300 µm under wet machining whereas cryogenic cooling reduced flank wear to 200 µm only but the insert attained around 220 µm average auxiliary flank wear under dry, 280 µm under wet machining and 145 µm under cryogenic cooling.

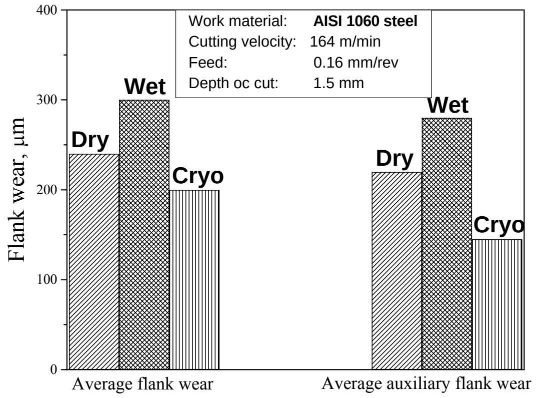
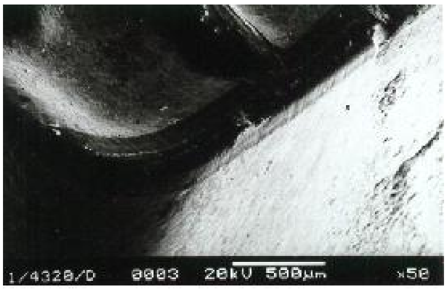
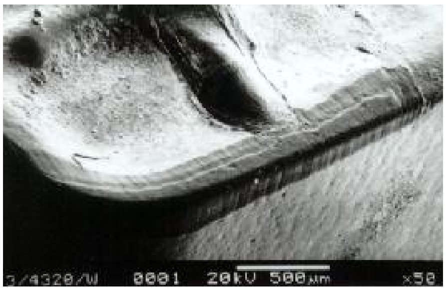


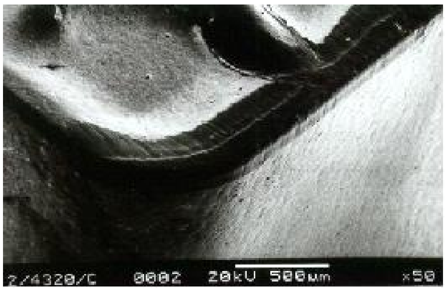
Fig 5. Flank wears developed on insert after machining steel for 64 minutes under different environments.



(a) Dry machining



(b) Wet machining



(c) Cryogenic machining
(d)

Fig 6. SEM views of worn out tip after 64 min of machining under different environments.

Fig.6 shows the SEM photographs of worn out insert used for machining steel bar for 64 minutes under dry, wet and cryogenic environments. No notch and groove wear were observed under all the three environments due to chemical inertness of alumina and TiCN. The main cutting edge has suffered minor micro fracturing under dry machining. The coating allowed less crater wear under all the three environments as it acts as good thermal and diffusion barrier. Cryogenic cooling expectedly reduced main flank and auxiliary flank wear.

The nature and extent of surface roughness in the longitudinal direction of the turned job depend mainly upon the geometry and condition of the auxiliary cutting edge including a part of the rounded nose. The value of surface roughness increases sharply with the increase in feed and decrease with increase in V_c. Built-up edge formation and vibration worsen the surface further.

The results shown in Fig.7 indicate that surface roughness increased substantially with the increase in feed when machined by both the tools and under both the environments. This can be attributed mainly to the roughness caused by the feed marks as explained earlier. It is also noted that surface roughness decreased to some extent with the increase in V_c possibly due to smoothening of the nose profile by adhesion and diffusion types wear.

However, surface roughness decreased to some extent though in different degree at different V_c and S_o when the job was machined under cryogenic cooling. This can be attributed to reduction in auxiliary flank wear due to retention of tool hardness through reduction in temperature by the liquid nitrogen jet specially that impinged along the auxiliary cutting edge.

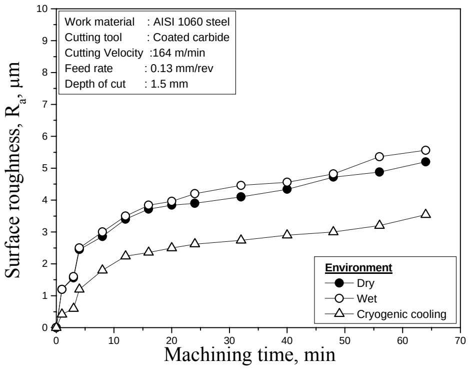


Fig 7. R_a value developed with machining time under different environments at cutting velocity, 164 m/min

Cryogenic cooling provided remarkable benefit in respect of controlling the increase in diameter of the finished job with machining time as can be seen in Fig.8. In plain turning, the finished job diameter generally deviates from its desired value with the progress of machining i.e. along the job-length mainly for change in the effective depth of cut due to several reasons which include wear of the tool nose, over all compliance of the Machine-Fixture-Tool-Work (M-F-T-W) system and thermal expansion of the job during machining followed by cooling. Therefore, if the M-F-T-W system is rigid, variation in diameter would be governed mainly by the heat and cutting temperature. With the increase in temperature the rate of growth of auxiliary flank wear and thermal expansion of the job will increase. Cryogenic cooling takes away the major portion of heat and reduces the temperature resulting decrease in dimensional deviation desirably.

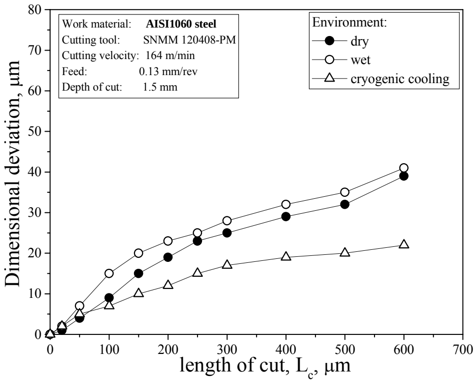


Fig 8. Variation in change in dimension with cutting length under different conditions at V_c, 164 m/min

4. CONCLUSIONS

Based on the results of the present experimental investigation the following conclusions can be drawn:

- The cutting performance of cryogenic machining is better than that of conventional machining with flood cutting fluid supply.
- Cryogenic cooling provides the benefits mainly by substantial reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges.
- Dry machining of steel caused maximum tool wear and surface roughness and wet machining did not show appreciable improvement.
- Cryogenic cooling by liquid nitrogen jets provided lesser tool wear, better surface finish and higher dimensional accuracy as compared to dry and wet machining.

5. ACKNOWLEDGEMENT

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