AN EXPERIMENTAL STUDY OF CRYOGENIC COOLING EFFECTS IN MACHINING AISI-4140 STEEL

N. R. Dhar and M. M. A. Khan..

ABSTRACT

Application of conventional cutting fluids do not serve the purposes effectively particularly under high cutting velocity and feed. Besides, such cutting fluids pollute the environment in high production machining and grinding. Cryogenic cooling seemed to be quite effective in reducing the high cutting temperature, which impairs product quality and reduces tool life. Cryogenic cooling is an environment friendly clean technology for desirable control of cutting temperature. The present work investigates the role of cryogenic cooling by liquid nitrogen jet on chip formation, cutting forces and cutting temperature in turning AISI 4140 steel under industrial speed-feed conditions. The experimental results indicate significant reduction in cutting temperature on application of cryogen. Such reduced temperature along with reduction in chip-tool contact length and favourable chip-tool interaction also provide significant reduction in cutting forces.

Keywords: Turning, Cryogenic cooling, Cutting temperature, Cutting forces

1. INTRODUCTION

Machining industries essentially try for high material removal rate (MRR) and product quality. The major problems in achieving high productivity and quality are caused by the high cutting temperature developed during machining at high cutting velocity and feed, particularly when the work material is difficult-to-machine. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface micro-cracks in addition to rapid oxidation and corrosion [1,2]. Generally, such problems are tried to be controlled by profuse cooling with soluble oil. But conventional cooling is not that effective, as the bulk chip-tool contact under high cutting velocity and feed prevents the fluid from entering the chip-tool interface, where temperature is maximum [3-7]. However, high-pressure jet of soluble oil, if applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent [7,8].

Besides providing only marginal technological benefits, the conventional cutting fluids pose a few major environmental problems [9]; like

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environmental pollution due to chemical break-down of the cutting fluid at high cutting temperature, biologically hazardous to operator due to bacterial growth [10] and water pollution and soil contamination during final disposal. Simply, the cost of disposal of used coolant has increased substantially and in Germany in 1994, it was estimated [9] to be one billion DM.

Possibility of controlling high cutting temperature in high production machining by some alternative methods have been reported, like tribologically modified cutting inserts [11], high pressure coolant injection technique [12] and CO_2 in the form of jet [13].

Application of cryogen for effective cooling without polluting the environment is becoming more and more popular [14-25]. But in addition to pollution control, the industries also reasonably insist economic viability through technological benefits in terms of product quality, tool life and saving power consumption by application of cryogenic cooling. So it has become essential to study the role of cryogenic cooling on cutting forces, cutting tool wear and quality of the product in machining and grinding where high cutting temperature is the major concern and optimize the cryogenic application to derive maximum benefits.

The review of the literature suggests that cryogenic cooling provides several benefits in machining and grinding. The objective of the present work is to experimentally investigate the influence of cryogenic cooling by liquid nitrogen jets on chip formation, cutting forces and temperature in machining AISI-4140 steel with integrated chip breaker type uncoated carbide inserts.

2. EXPERIMENTAL INVESTIGATIONS

AISI 4140 steel rolled stock of initial diameter 200 mm and length 750 mm was straight turned in a high power rigid HMT lathe by uncoated carbide inserts of two different integrated chip breaker geometry at industrial speed-feed combination under dry and cryogenic cooling conditions to study the role of cryogenic cooling in respect of chip formation and cutting forces as well as cutting temperature. The experimental setup is schematically shown in Fig.1. Table-1 provides the detailed experimental conditions.

Liquid nitrogen jets were applied almost along the main and auxiliary cutting edges. Two jets have been used mainly to target the rake surface and flank surface along the main cutting edge and to protect the auxiliary flank to enable better surface finish and dimensional accuracy. Two different integrated chip breaker geometry cutting insert were used to study the effect of such geometry on effectiveness of cryogenic cooling. The process parameters as indicated in Table-1 were selected as per industrial practice and recommendation of tool manufacturers for machining AISI 4140 steel.

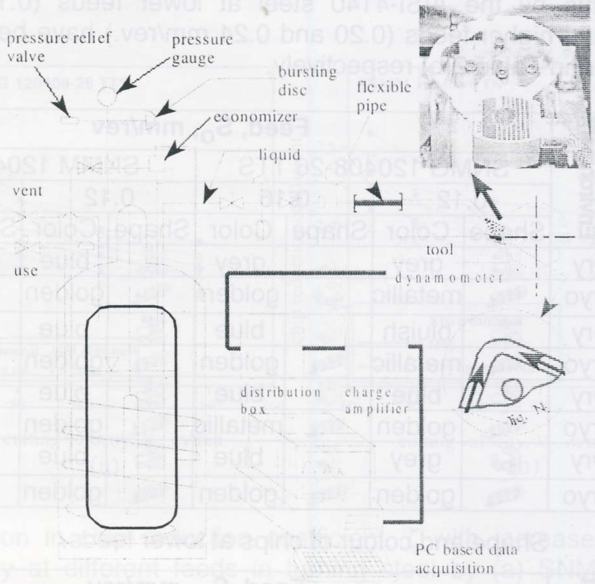


Fig.1 Schematic layout of the experimental set-up

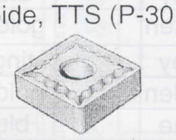
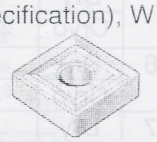
Machine tool	NH22 HMT Lathe, India, 11 kW
Work specimen	AISI-4140 steel (C-0.43%, Mn-0.67%, Si-
Material	0.20%, Cr-1.05%, Mo-0.15%)
Size	φ200 X 750 mm (Hardness: 252 BHN)
Cutting inserts	Carbide, TTS (P-30 ISO specification), WIDIA
	 
	SNMG 120408-26 **SNMM 120408**
Tool holder	PSBNR 2525 M12 (ISO specification)
Working tool geometry	-6, -6, 6, 6, 15, 75, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	67 to 137 m/min
Feed rate, S_o	0.12, 0.16, 0.20 and 0.24 mm/rev
Depth of cut, t	1.5 mm
Environment	Dry and cryogenic cooling by liquid nitrogen

Table-1 Experimental conditions

The chip samples collected while turning the steels by the different inserts of configuration SNMG and SNMM at different V_c-S_o combinations under both dry and cryogenic cooling condition have been visually examined and categorized with respect to their shape and colour. The results of such categorization of the chips produced at different conditions and environments by the AISI-4140 steel at lower feeds (0.12 and 0.16 mm/rev.) and higher feeds (0.20 and 0.24 mm/rev.) have been shown in Table 2(a) and Table 2(b) respectively.

V_c, m/min	Environment	Feed, S_o, mm/rev							
		SNMG 120408-26 TTS				SNMM 120408 TTS			
		0.12		0.16		0.12		0.16	
		Shape	Color	Shape	Color	Shape	Color	Shape	Color
67	Dry		grey		grey		blue		grey
	Cryo		metallic		golden		golden		golden
81	Dry		bluish		blue		blue		grey
	Cryo		metallic		golden		golden		copper
106	Dry		blue		blue		blue		grey
	Cryo		golden		metallic		golden		blue
137	Dry		grey		blue		blue		grey
	Cryo		golden		golden		golden		blue

Table 2(a) Shape and colour of chips at lower feeds.

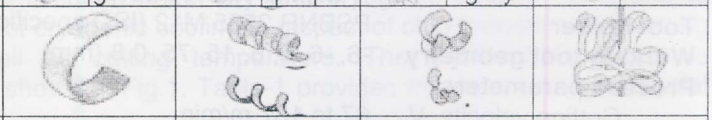
V_c, m/min	Environment	Feed, S_o, mm/rev							
		SNMG 120408-26 TTS				SNMM 120408 TTS			
		0.20		0.24		0.20		0.24	
		Shape	Color	Shape	Color	Shape	Color	Shape	Color
67	Dry		blue		blue		blue		grey
	Cryo		golden		golden		golden		copper
81	Dry		grey		blue		grey		grey
	Cryo		golden		golden		blue		blue
106	Dry		grey		tinge		grey		grey
	Cryo		golden		golden		blue		blue
137	Dry		blue		blue		blue		blue
	Cryo		golden		purple		grey		blue
Chip shape									
Group		Half turn		Tubular/helical		Spiral		Ribbon	

Table 2(b) Shape and colour of chips at higher feeds.

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For the given tool geometry and cutting conditions, the value of ζ depends upon the nature of chip-tool interaction, chip contact length and chip form, all of which are expected to be influenced by cryogenic cooling in addition to the levels of V_c and S_o. The variation in value of ζ with change in tool configuration, V_c and S_o as well as machining environment evaluated for AISI 4140 steel has been plotted and shown in Fig.2.

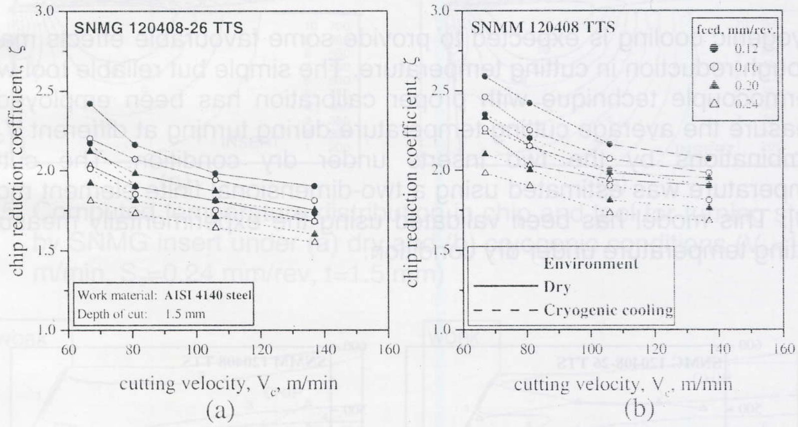


Fig.2 Variation in chip reduction coefficient, ζ with increase in cutting velocity at different feeds in turning steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions

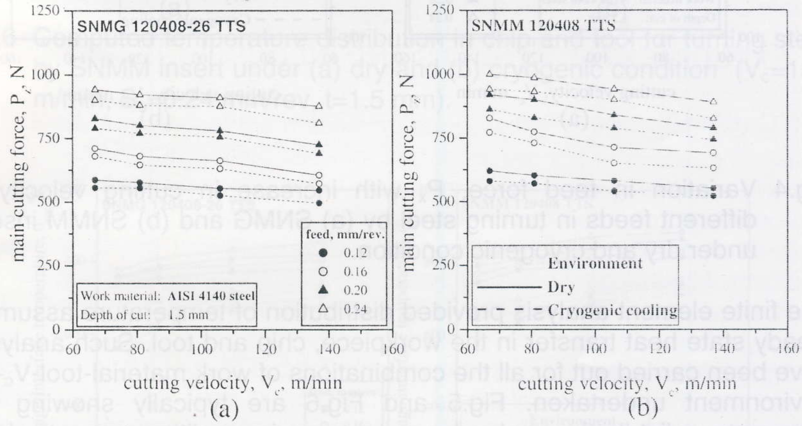


Fig.3 Variation in main cutting forces, P_z with increase in cutting velocity at different feeds in turning steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions

The tangential or main component, P_z and the feed or axial component, P_x of the cutting force were monitored by a 3-D dynamometer (Kistler 3-component dynamometer) and recorded in a PC using a data acquisition system (PCL 818 HG Multifunction 12 bit highgain DAS card: Sampling frequency 2000 Hz) during turning the steel by the carbide inserts (a) SNMG and (b) SNMM under different V_c and S_o and have been graphically shown in Fig.3 and Fig.4 respectively.

Cryogenic cooling is expected to provide some favourable effects mainly through reduction in cutting temperature. The simple but reliable tool-work thermocouple technique with proper calibration has been employed to measure the average cutting temperature during turning at different V_c-S_o combinations by the two inserts under dry condition. The cutting temperature was estimated using a two-dimensional finite element model [26]. This model has been validated using the experimentally measured cutting temperature under dry condition.

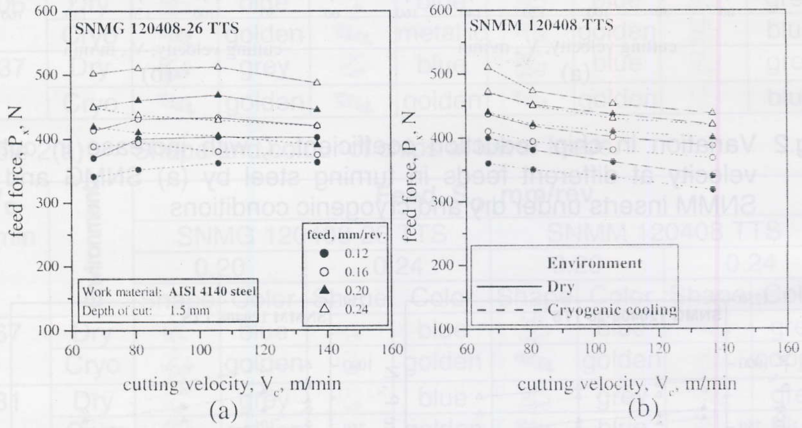
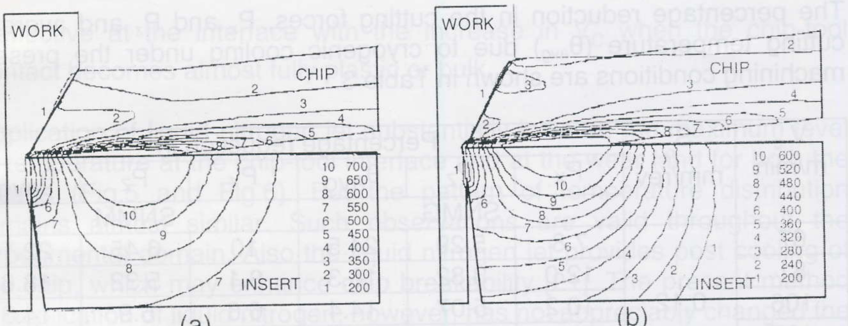


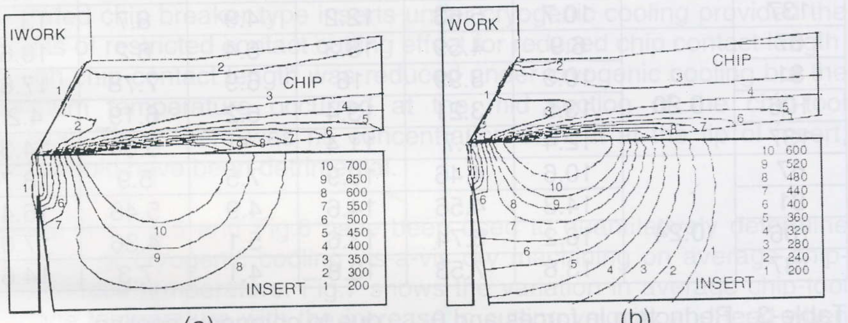
Fig.4 Variation in feed force, P_x with increase in cutting velocity at different feeds in turning steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic condition.

The finite element analysis provided distribution of temperature assuming steady state heat transfer in the workpiece, chip and tool. Such analyses have been carried out for all the combinations of work material-tool-V_c-S_o-environment undertaken. Fig.5 and Fig.6 are typically showing the temperature distribution under dry and cryogenic condition respectively by SNMG and SNMM inserts. The effect of cryogenic cooling on average chip-tool interface temperature in turning steel by the two types of inserts at different V_c and S_o under dry and cryogenic condition has been shown in Fig.7.



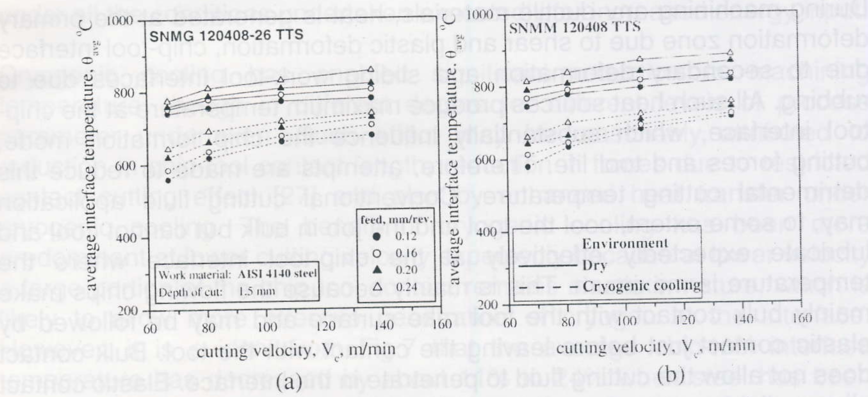
(a) (b)

Fig.5 Computed temperature distribution in chip and tool for turning steel by SNMG insert under (a) dry and (b) cryogenic conditions (V_c=137 m/min, S_o=0.24 mm/rev, t=1.5 mm)



(a) (b)

Fig.6 Computed temperature distribution in chip and tool for turning steel by SNMM insert under (a) dry and (b) cryogenic condition (V_c=137 m/min, S_o=0.24 mm/rev, t=1.5 mm).



(a) (b)

Fig.7 Variation in θ_{avg} that of V_c and S_o in turning steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions.

The percentage reduction in the cutting forces, P_x and P_z and average cutting temperature (θ_{avg}) due to cryogenic cooling under the present machining conditions are shown in Table 3.

V_c m/min	S_o mm/rev	Percentage reduction in					
		P_X	P_Z	θ_{avg}	P_X	P_Z	θ_{avg}
		SNMG			SNMM		
67	0.12	7.8	5.29	24.5	10	6.45	22.1
81		12.0	3.82	18.3	8.1	5.32	18.6
106		10.2	5.07	14.4	6.6	6.9	14.3
137		9.7	9.19	13.1	6.5	5.45	12.4
67	0.16	6.1	4.23	22.2	6.2	6.76	20.2
81		8.6	5.15	18.4	5.7	5.68	18.2
106		12.2	4.83	14.3	5	8.71	15.0
137		10.7	5.63	12.2	4.9	8.7	13.1
67	0.20	6.9	4.59	18.3	6.4	6.2	18.6
81		10.9	3.99	16	6.9	7.78	17.6
106		13.5	3.21	13.4	6.2	6.19	4.2
137		12.4	4.7	11.4	5	5.84	14.3
67	0.24	10.6	4.46	16.9	7.5	5.9	18.7
81		14.3	4.56	14.6	4.9	5.48	16.4
106		16.2	3.74	13.6	5.1	4.36	17.0
137		13.8	7.53	13.8	4.1	7.3	14.6

Table-3 Reduction in forces and θ_{avg} due to cryogenic cooling

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

On Cutting Temperature

During machining any ductile materials, heat is generated at the primary deformation zone due to shear and plastic deformation, chip-tool interface due to secondary deformation and sliding 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.

Application of liquid nitrogen jet substantially lowered the maximum level of temperature at the chip-tool interface and at the wear land for both the inserts (Fig.5 and Fig.6). But the pattern of temperature distribution remains almost similar. Such observations are valid throughout the experimental domain. Also the liquid nitrogen jet provides post cooling of the chip, which may enhance chip breakability [21]. The present method of application of liquid nitrogen, however, has not appreciably changed the shear plane temperature.

Under cryogenic cooling, the contact side of the chip was cooled leading to closer chip curling and reduction in chip-tool contact length. The integrated chip breaker type inserts under cryogenic cooling provided the benefits of restricted contact cutting effect for reduced chip contact length. Though chip contact length was reduced under cryogenic cooling but the maximum temperature occurred at the mid section of the chip-tool interface. Thus, there was no concentration of heat at the tip of insert, which would have been detrimental.

Figures like Fig.5 and Fig.6 have been used to quantitatively determine the effect of cryogenic cooling vis-a-vis dry machining on average chip-tool interface temperature. Fig.7 shows the variation in average chip-tool interface temperature with the increase in cutting velocity and feed when steel is turned by the pattern type (SNMG) and groove type (SNMM) insert under both cryogenic and dry conditions.

Fig.7 clearly shows that the machining temperature significantly increased with the increase in cutting velocity and feed, though in different degree, under all the conditions undertaken expectedly for increased energy input.

Cryogenic cooling has enabled significant reduction in machining temperature, though in different degree for different levels of process parameter undertaken. Such effect may be reasonably attributed to reduction in chip-tool contact length, reduction in forces due to restricted contact cutting effect [27] and also by enhanced heat transfer under cryogenic cooling. The benefit of cryogenic cooling has been more predominant at lower cutting velocity expectedly because at lower velocity a large portion of the chip-tool contact remains elastic in nature, which is likely to allow more effective penetration of cryogen at the interface. However, it is evident from Fig.7 that the average chip-tool interface temperature has decreased by about 11% to 24% when steel has been machined under cryogenic cooling. 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 Table-3. The percentage reduction in the average cutting temperature gradually decreased with the increase in V_c more or less truly under all the values of S_o when the steel rod was machined under cryogenic cooling by the SNMM type insert unlike when machined by the SNMG type. This indicates that the geometry of the cutting insert plays significant role on the effectiveness of cryogenic cooling. It seems the increased bulk contact of the chips with the tool with the increase in V_c did not allow significant entry of even the liquid nitrogen jets in case of the SNMM insert whose cutting edge geometry allowed intimate contact of the chip over the chip-tool contact length. Only possible reduction in the chip-tool contact length by the cryogenic jets, particularly that which comes along the auxiliary cutting edge, could reduce the temperature to some extent particularly when the chip velocity was high due to higher V_c.

Machining Chips

The pattern of chips in machining ductile metals generally depends upon the mechanical properties of the work material, tool geometry particularly rake angle, levels of V_c and S_o, nature of chip-tool interaction and the cutting environment. In absence of chip breaker, length and uniformity of chips increase with the increase in ductility and softness of the work material, tool rake angle and cutting velocity unless the chip-tool interaction is adverse causing intensive friction and built-up edge formation.

Table 2(a) and Table 2(b) show that the steel, when machined by the pattern type SNMG inserts under dry condition produced ribbon type continuous chips at low feed (0.12 mm/rev) and more or less half turn chips at higher feeds. The geometry of the SNMG insert is such that the chips of this steel first came out continuously got curled along normal plane and then hitting at the principal flank of this insert broke into pieces with regular size and shape. When machined under cryogenic cooling the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of inert nitrogen due to cryogenic application enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation.

The colour of the chips have also become much lighter i.e. metallic or golden from blue or grey depending upon V_c and S_o due to reduction in cutting temperature by cryogenic cooling.

Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. The degree of chip thickening which is assessed by chip reduction coefficient, ζ, plays sizeable role on cutting forces and hence on cutting energy requirements and cutting temperature.

Fig.2 shows that cryogenic cooling has reduced the value of particularly at lower values of V_c and S_o when both the inserts machined the steel rod. By cryogenic applications, ζ is reasonably expected to decrease for reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature and also possibly for removal of oxygen from the cutting zone by nitrogen. In this case, more effective cryogenic cooling seemingly enabled larger reduction in at lower V_c and S_o. But close curling of the chips due to post cooling by nitrogen jets may, on the other hand, tend to increase to some extent.

Cutting Forces

The nature of variation in the cutting forces P_z and P_x observed during turning the steel rod by the two different types inserts at different V_c and S_o under both dry and cryogenic cooling conditions are shown in Fig.3 and Fig.4 respectively.

The magnitude and pattern of the cutting forces is one of the most important machinability indices because that plays vital roles on power and specific energy consumption, product quality and life of the salient numbers of the Machine-Fixture-Tool systems. Design of the Machine-Fixture-Tool-Work systems also essentially need to have the knowledge about the expected characteristics of the cutting forces. Therefore, it is reasonably required to study and assess how the cutting forces and tool life are affected by cryogenic cooling with liquid nitrogen, which is primarily aimed at environment friendly machining.

Fig.3 and Fig.4 are clearly showing that both P_z and P_x have uniformly decreased with the increase in V_c more or less under all the feeds, for both the tools and environments undertaken as usual due to favourable change in the chip-tool interaction resulting in lesser friction and intensity or chances of built-up edge formation at the chip-tool interface. In machining ductile metals like steels by carbide tools, which are not chemically inert like ceramics, the chip material under elevated temperature and high pressure sticks in their layer on the tool surface by adhesion and diffusion and often resulting in gradual piling of the strain hardened layers forming built-up edge near the cutting edge. After growing to certain size, the built-up edge gets separated from the tool by the increased transverse force. Both the formation and frequent separation of built-up edge are detrimental because it not only raises and fluctuates the cutting forces but also impairs the finished surface and reduces tool life.

It is evident from Fig.3 and Fig.4 that both P_z and P_x decreased sizeably due to application of liquid nitrogen jet more or less at all the V_c-S_o combinations and for both the inserts. This improvement can be reasonably attributed to reduction in the cutting temperature particularly near the main cutting edge where seizure of chips and formation or tendency of formation of built-up edge is more predominant. In this respect, the liquid nitrogen jet impinged along the main cutting edge seems to be more effective in cooling the neighborhood of the main cutting edge.

During machining, the shear strength of the ductile type work material at the cutting zone in one hand increases due to compression and straining and on the other hand decreases due to softening by the cutting temperature if it is sufficiently high. But again along with softening, the chip material becomes sticky for which the friction force and hence the cutting force may tend to increase. The overall effect of all such factors on the magnitude of the cutting forces will depend on the nature of the work material and the level of the cutting temperature. Therefore, it seems that cryogenic cooling had ultimately favourable effect on the behavior of the present alloy steel in respect of cutting forcers for which cryogenic cooling enabled reduction in the cutting forces to some extent even when built-up edge was not visible.

The percentage reduction observed in P_z and P_x due to cryogenic application during turning the present steel by the SNMG and SNMM inserts at different V_c and S_o are given in Table-3. The table shows that there is no definite trend in the role of variation in V_c and S_o as well as the type of inserts on the percentage reduction in P_z and P_x unlike on that in cutting temperature. The degree of reduction in the cutting forces seems to have been governed combinedly by the levels of V_c and S_o and the tool geometry, which together not only controlled the degree of cooling by the liquid nitrogen jets but also influenced the indirect effects of cryogenic cooling like reduction in chip-tool contact length, break-in wear at the cutting edges, close curling of the chips, all of which might have contributed in reducing the cutting forces. The randomness in percentage reduction in P_z and P_x (Table-3) might be also indebted to the random formation and dislodgement of the built-up edge, whatever be its size and bond strength. However, more in depth study is needed to explore the actual role of the different parameters on the effect of cryogenic cooling in machining different materials by different tools.

4. CONCLUSIONS

i. Cryogenic cooling by liquid nitrogen provides not only friendly working environment and bulk cooling of the tool and the job but also, if properly employed, some technological benefits like reduction in the cutting forces, favourable chip formation and retention of cutting edge sharpness over longer period.

ii. The degree of technological benefits of cryogenic application in machining a ductile metal depends upon how the cryogen is applied, the cutting tool geometry and the levels of the machining process parameters.

iii. Cryogenic cooling improved the machinability of the steel mainly through reduction in the cutting zone temperature and favourable change in chip-tool interaction.

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