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The influence of cryogenic cooling on tool wear, dimensional accuracy and surface finish in turning AISI 1040 and E4340C steels

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Abstract

In all machining operations, tool wear is a natural phenomenon and it eventually leads to tool failure. The growing demands for high productivity of machining need use of high cutting velocity and feed rate. Such machining inherently produces high cutting temperature, which not only reduces tool life but also impairs the product quality particularly when the work piece is quite strong, hard and heat resistant. Conventional cooling methods are not only ineffective but also deteriorate the working environment by producing harmful gasses and smokes. Attempts have already been initiated to control the pollution problem by cryogenic cooling which also enables get rid of recycling and disposal of conventional fluids and possible damage of the machine parts by corrosion, etc.

This paper deals with experimental investigation on the role of cryogenic cooling by liquid nitrogen jet on tool wear and product quality in plain turning of AISI 1040 and E4340C steel at industrial speed–feed combinations by two types of carbide inserts of different geometry. The encouraging results include significant reduction in tool wear rate, dimensional inaccuracy and surface roughness by cryogenic cooling application mainly through reduction in the cutting zone temperature and favourable change in the chip–tool and work–tool interaction.

Keywords: Cryogenic cooling; Liquid nitrogen jet; Tool wear; Surface finish; Dimensional accuracy

1. Introduction

Machining industries essentially try for high material removal rate (MRR) and products 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 rate 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 microcracks in addition to rapid oxidation and corrosion [1,2]. Currently, this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper cutting fluid application and using heat resistant cutting tools.

High cutting zone temperature is generally tried to be controlled by employing flood cooling by soluble oil. In high speed–feed machining, conventional cutting fluid application fails to penetrate the chip–tool interface and thus cannot remove heat effectively [3–5]. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip–tool interface to provide lubrication and cooling [6]. In high speed machining of Inconel and titanium alloys, cutting fluids reportedly [7] failed to reduce cutting temperature and improve tool life effectively. However, high pressure jet of soluble oil, when applied [8,9] at the chip–tool interface, could reduce cutting temperature and improve tool life to some extent.

Besides providing only marginal technological benefits, the conventional cutting fluids pose a few major environmental problems [10]:

- environmental pollution due to chemical break-down of the cutting fluid at high cutting temperature;
- biologically hazardous to operator due to bacterial growth [11];
- requirements of additional system for pumping, local storage, filtration, recycling, chilling and large space;
- 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 [10] to be one billion DM.

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Possibilities of controlling high cutting temperature in high production machining by some alternative methods have been reported. Cutting forces and temperature were found to reduce while machining steel with tribologically modified carbide inserts [12]. High pressure coolant injection technique [13] not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50%. Application of CO_2 in the form of liquid jet at high pressure also enabled [14] some reduction in cutting forces.

Some works have recently been done on cryogenic cooling by liquid nitrogen jet in machining and grinding some steel of common use [15–21]. Cryogenic cooling provided less cutting forces, better surface finish and improved tool life compared to dry machining [15–18]. Detailed grinding studies [19–21] revealed similar benefits with improved surface integrity compared to dry grinding and grinding with soluble oil.

The earlier work [22–25] of late 1960s and early 1970s 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 by diamond tools were also reported [26]. The favourable role of cryogenic cooling in chip breaking and reducing cutting temperature in turning [27] and overall improvement in face milling [28] has been reported. Even in turning of reaction bonded silicon nitride by CBN inserts, cryogenic cooling provided improved tool life [29,30].

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 tool wear, dimensional deviation and surface roughness in turning AISI 1040 and E4340C steel at industrial speed–feed conditions by carbide inserts and compare the effectiveness of cryogenic cooling with that of dry machining.

2. Experimental conditions and procedure

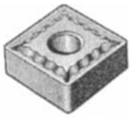
For the present experimental studies, two types of steel rods (AISI 1040 and E4340C steel) of initial diameter 200 mm and length 750 mm were plain turned in a rigid and powerful HMT lathe by two types of carbide inserts of different geometry at industrial speed–feed combinations under both dry and cryogenic cooling conditions. The experimental conditions are given in Table 1.

Two different types of carbide inserts have been taken to study the role of cutting tool geometry on the effectiveness of cryogenic cooling. The ranges of the cutting velocity (V_c) and feed rate (S_0) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed.

The liquid nitrogen delivery system is schematically shown in Fig. 1. For cryogenic cooling, liquid nitrogen in the form of thin but high speed jets were impinged from a specially designed nozzle towards the cutting zone along two directions almost parallel to the cutting edges.

The cutting insert was withdrawn at regular intervals to study the pattern and extent of wear on main and auxiliary flanks for all the trials. The average width of the principal flank wear, V_B and auxiliary flank wear, V_S were measured

Table 1
Experimental conditions

Machine tool	NH22 HMT Lathe, 11 kW (15 hp), India
Work specimens	
Materials	AISI 1040 steel AISI E4340C steel
Application	Soft and hard gears and shafts
Size	Ø 200 mm × 750 mm
Cutting tools (inserts)	
Cutting inserts	Carbide, TTS (P-30 ISO specification), WIDIA  **SNMG 120408-26**  **SNNM 120408**
Tool holder	PSBNR 2525M12 (ISO specification)
Working tool geometry ()	−6, −6, 6, 6, 15, 75 and 0.8 mm
Process parameters	
Cutting velocity, V_c	60–150 m/min
Feed rate, S_0	0.12, 0.16, 0.20 and 0.24 mm/rev
Depth of cut, t	1.5 m and 2.0 mm
Environment	Dry and cryogenic cooling

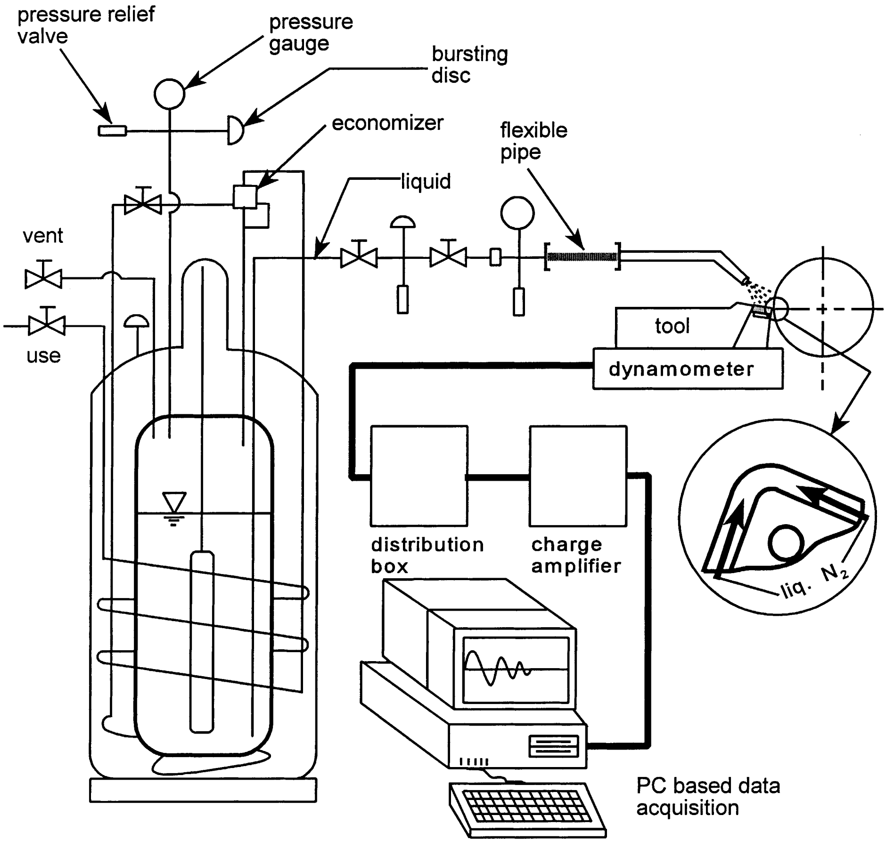


Fig. 1. Experimental set-up under cryogenic cooling.

using in inverted metallurgical microscope (Olympus, Model MG) fitted with micrometer of least count 1 μm.

The surface roughness and variation in finished diameter along the job-axis were monitored by a Talysurf (model Surtronic 3P, Rank Taylor Hobson) using a sampling length of 0.8 mm and precision dial gauge, respectively. At the end of full cut, the cutting inserts were inspected under scanning electron microscope (Model: JSM 5800, JEOL, Japan).

3. Experimental results and discussion

3.1. On cutting temperature

The liquid nitrogen jets at temperature −196°C were apparently supposed to cool the hot cutting zone drastically but actually the effect has been much less reasonably because the cryogen jets, even under high flow-speed, cannot fully penetrate into the intimate chip–tool contact (mostly plastic in nature) area where the temperature is maximum. However, the cryogen streams are expected to reduce the cutting temperature significantly by coming closer to the chip–tool plastic contact zone through the flanks and the small elastic contact zone (ahead the plastic contact zone) by capillary effect. The average cutting temperature under dry machining was conveniently measured by tool–work thermo-couple principle. But, some scatter in temperature measurement was observed when liquid nitrogen was employed. Then, a finite element model was developed to estimate the distribution of cutting temperature within the cutting tool, job and chip. The model takes into account the variation in the material properties with temperature and mass and heat transfer associated with job and chip movement. The model has been validated with the average cutting temperature obtained under dry machining. The same model has been used to estimate average cutting temperature under cryogenic cooling with appropriate connective boundary conditions [18]. Table 2 shows the percentage reduction observed in average cutting temperature due to cryogenic cooling for the different work–tool and V_c–S_0 combinations.

Table 2 indicates that cryogenic cooling could reduce the average cutting temperature (θ_{avg}) though not drastically but substantially and the work material characteristics, tool geometry and the levels of V_c and S_0 have significant influence on the effectiveness of such cryogenic cooling.

Cryogenic cooling appears to be more effective in case of the AISI 1040 steel possibly for favourable shape and lesser stiffness of its chips.

Compared to the SNMG insert, the SNMM insert having wide and deep grooves parallel to its cutting edges seemed to provide better cryogenic cooling effect particularly when the work material is AISI 1040 steel. It is also evident from

Table 2
Reduction in cutting temperature due to cryogenic cooling cutting

Feed (mm/rev)	Cutting velocity (m/min)	Percentage reduction in average cutting temperature			
		AISI 1040 steel, insert		AISI E4340C steel, insert	
		SNMG	SNMM	SNMG	SNMM
0.12	66	27.53	33.93	17.80	19.35
	85	25.55	30.91	17.20	15.31
	110	20.67	21.44	11.20	14.29
	144	14.97	18.79	19.00	12.03
0.16	66	19.28	33.31	15.50	18.83
	85	19.43	28.75	14.90	15.27
	110	16.87	21.34	11.10	12.16
	144	13.79	20.30	19.50	11.19
0.20	66	16.54	27.24	13.20	18.51
	85	16.23	24.64	15.30	14.29
	110	14.98	23.38	12.80	11.13
	144	14.46	19.79	17.00	10.76
0.24	66	16.60	25.00	12.00	17.26
	85	16.86	27.53	13.90	13.27
	110	16.66	24.21	12.20	9.49
	144	15.36	24.33	16.40	10.37

Table 2 that cryogenic cooling effect slightly decreases with the increase in V_c and S_0. This may be attributed to the fact that with the increase in V_c and S_0, V_c in particular, the chip–tool contact tends to become fully plastic obstructing penetration of the cryogen into the hot chip–tool interface.

Apparently, more drastic reduction in θ_{avg} is expected by employing liquid nitrogen but actually it is not so because the cryogen could not reach the intimate chip–tool contact zone. However, during machining at lower V_c when the chip–tool contact is partially elastic, where the chip leaves the tool, liquid nitrogen is dragged in that elastic contact zone in small quantity by capillary effect and is likely to enable more effective cooling. With the increase in V_c the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip–tool interface. This is more or less reflected also in the results shown in Table 2. Cryogenic cooling effect also improved to some extent with the decrease in feed particularly at lower cutting velocity as can be seen in Table 2. Possibly, the thinner chips, specially at lower chip velocity, are slightly pushed up by the cryogen jet coming from opposite direction and enables it come closer to the hot chip–tool contact zone to remove heat more effectively. Further, at high velocity, the coolant may not get enough time to remove the heat accumulated at the cutting zone resulting in less reduction in temperature under cryogenic cooling at high cutting velocity.

3.2. On cutting tool wear

Productivity and economy of manufacturing by machining are significantly influenced by life of the cutting tools. Cutting tools may fail by brittle fracturing, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wear. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in Fig. 2 due to continuous interaction and rubbing with the chips and the work surfaces, respectively. 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, like 0.3 mm. Therefore, attempts should be made to reduce the rate of growth of flank wear (V_B) in all possible ways without sacrifice in MRR.

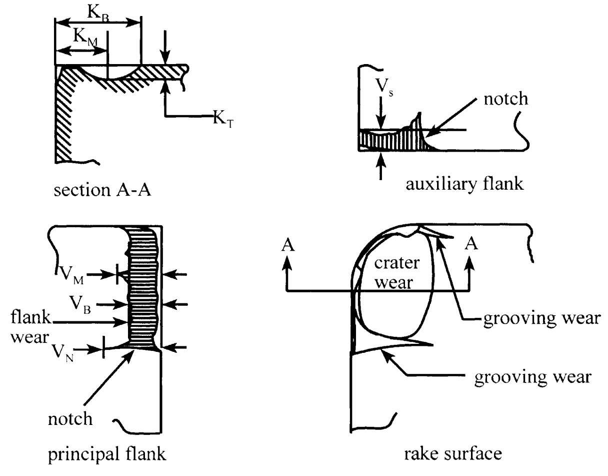
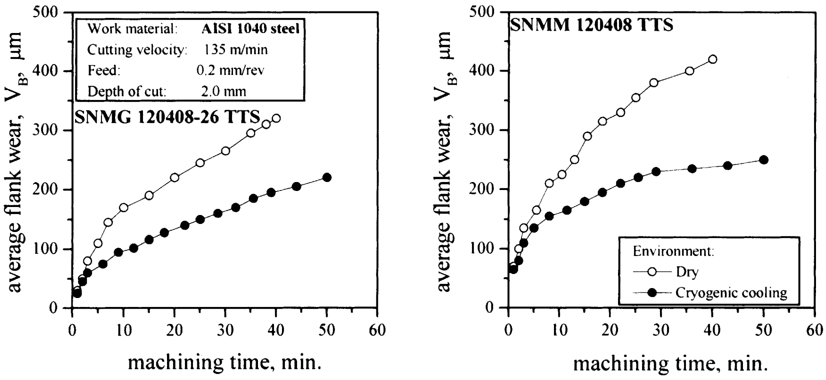


Fig. 2. Geometry and major features of wear of turning tools.



(a) (b)

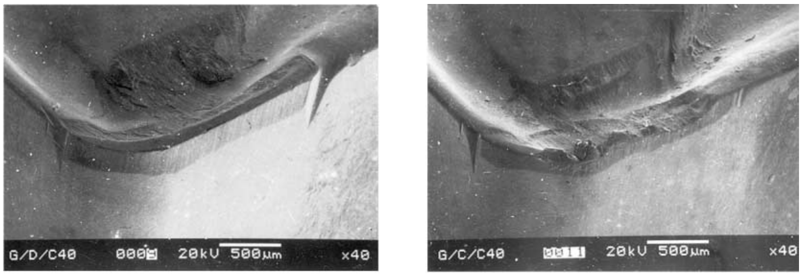
Fig. 3. Growth of average flank wear, V_B in (a) SNMG and (b) SNMM inserts during machining AISI 1040 steel at cutting velocity, 135 m/min under dry and cryogenic conditions.

It is already mentioned that wear of cutting tools are generally quantitatively assessed by the magnitudes of V_B, V_S, K_T, etc. shown in Fig. 2, out of which V_B is considered to be the most significant parameter at least in R&D work.

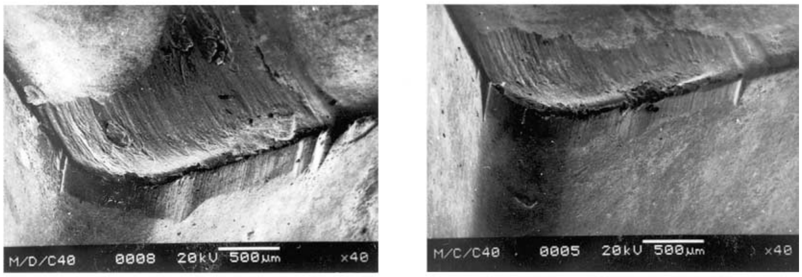
Fig. 3 clearly reveals that cryogenic cooling has reduced V_B remarkably in machining AISI 1040 steel and more profoundly when machined by the SNMM inserts. This is reasonably attributed to extremely cool and inert atmosphere provided by the liquid nitrogen jets, which could, at least partially, reach the work–tool interfaces, unlike chip–tool interface. The deep grooves parallel to the cutting edges of the SNMM inserts are likely to help entry of larger fraction of the liquid nitrogen jets at the flank surfaces. It was noted earlier that average cutting temperature decreased by cryogenic cooling to the maximum extent in case of AISI 1040 steel (Table 2) and more so when machined by SNMM inserts. This might have also contributed to so much reduction in V_B.

Fig. 3 reveals that during machining AISI 1040 steel by the SNMG insert under cryogenic cooling, V_B grew quite slowly and uniformly, but after about 45 min of machining chipping started at the main cutting edge of the insert, as can be seen in Fig. 4, possibly for thermal stressing due to non-uniform cooling within the small region. Sudden disturbances due to chip debris may also cause such chipping of the cutting edge. The SNMM insert was not found to suffer from such chipping.

In machining research, a cutting tool is generally said to have failed when its V_B reaches a specific value, mostly 0.3 mm. It is very important to note in Fig. 3 that tool life

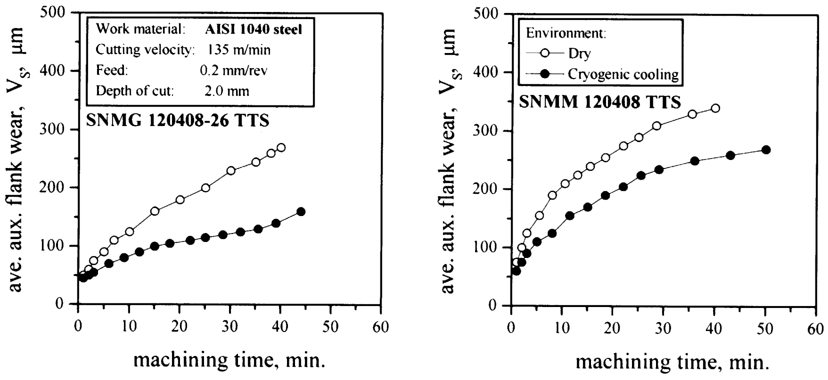


Dry machining, 40min (a) Cryogenic Machining, 50mm



Dry machining, 40min (b) Cryogenic Machining, 50mm

Fig. 4. SEM views of worn out tip of (a) SNMG and (b) SNMM inserts after machining AISI 1040 steel under dry and cryogenic cooling conditions.



(a) (b)

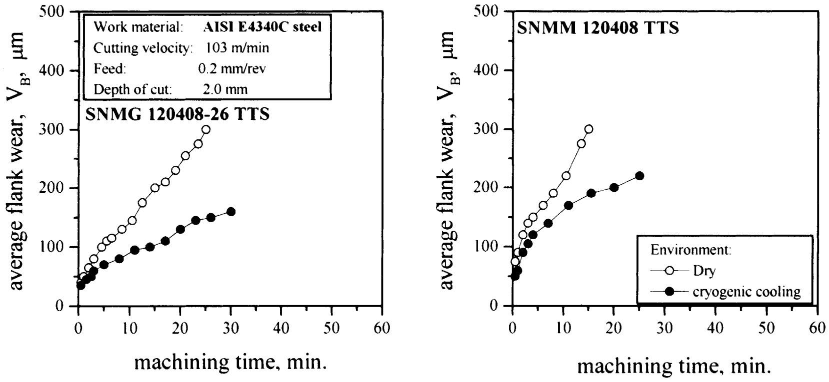
Fig. 5. Growth of average auxiliary flank wear, V_S with time in machining AISI 1040 steel under dry and cryogenic conditions by (a) SNMG and (b) SNMM inserts.

has improved from 35 min to much beyond 50 min in case of SNMG inserts and from about 17 to beyond 50 min in case of SNMM inserts, i.e. almost by two to three times increase in tool life have been possible by cryogenic cooling by liquid nitrogen. Fig. 4 also depicts how flank notch wear, V_N remarkably decreased due to cryogenic cooling. Deep notching, if forms, not only raises cutting forces but also may cause catastrophic tool failure prematurely and randomly, which is extremely harmful and undesirable for the present days' sophisticated and expensive manufacturing systems. So, proper cryogenic cooling is expected also to enhance reliability and safely of machining processes and systems.

Figs. 4 and 5 show the beneficial role of cryogenic cooling on the auxiliary flank wear, V_S the nature and extent of which affects dimensional accuracy and surface finish of the turned job.

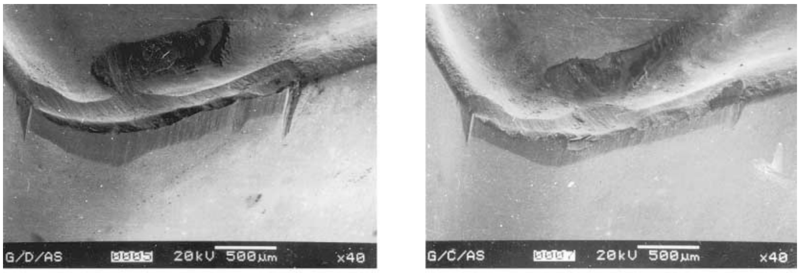
Fig. 6 shows that V_B grew quite fast in both the inserts in machining AISI E4340C steel expectedly for its higher strength and hardness. But cryogenic cooling enabled sharp reduction in V_B with the progress of machining. In uninterrupted machining of ductile metals by tools like carbides at reasonably high V_c and S_0, crater wear is governed mainly by adhesion and diffusion for rubbing at higher stresses and temperature and flank wear mainly by abrasion for lesser pressure and temperature. But adhesion and diffusion type temperature sensitive wear may also occur, in addition to abrasion wear, at the tool flanks if the flank temperature becomes high. Turning of ductile but strong metal like AISI E4340C steel at reasonably high V_c (103 m/min) and S_0 (0.2 mm/rev) under dry condition is expected to cause sufficiently high temperature at the tool flanks. Therefore, adhesion and diffusion are also likely to have contributed in the flank wear in the present case, and cryogenic cooling seemingly prevented such temperature sensitive adhesion and diffusion as well as reduced abrasion wear.

It clearly appears from Fig. 7 that the principal flank of the SNMG and SNMM inserts attained wide and deep notching even within 25 and 15 min, respectively while dry machining of AISI E4340C steel expectedly for high strength and hardness of this steel. But such detrimental notching remarkably decreased, as can be seen in Fig. 7, when liquid nitrogen was employed, which reduced both abrasive and



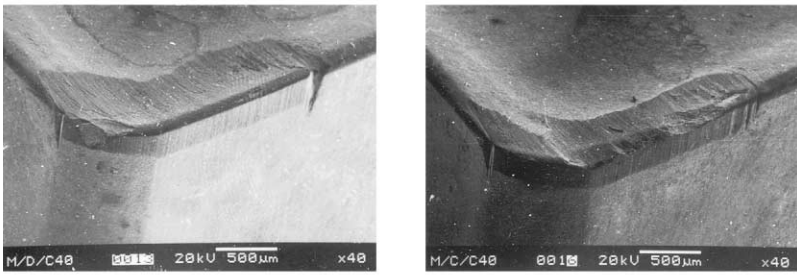
(a) (b)

Fig. 6. Growth of average flank wear, V_B in (a) SNMG and (b) SNMM inserts during machining AISI E4340C steel at cutting velocity, 103 m/min under dry and cryogenic conditions.



Dry machining, 25min

Cryogenic Machining, 30min



Dry machining, 25min

Cryogenic Machining, 30min

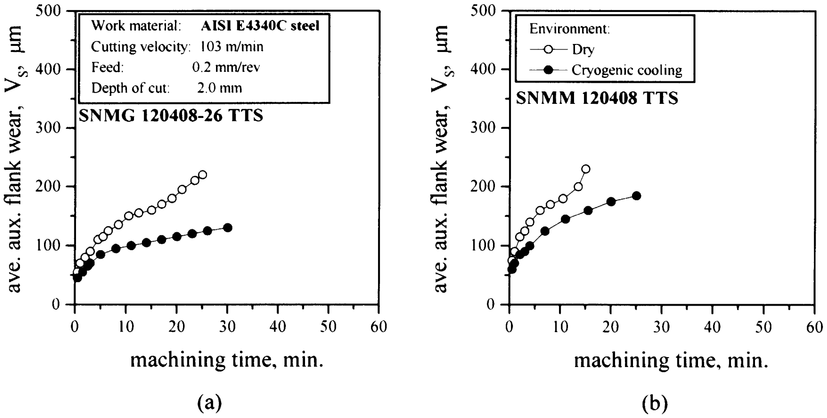
Fig. 7. SEM views of worn out tip of (a) SNMG and (b) SNMM inserts after machining AISI E4340C steel under dry and cryogenic cooling conditions.

chemical wear at the tool flanks. Fig. 7 also shows that flank wear occurred more or less uniformly along the main cutting edge of both the tools and under both the environments in machining the AISI E4340C steel.

Reduction in average flank wear (V_S) also in SNMG and SNMM inserts enabled by present cryogenic cooling in machining AISI E4340C steel can be seen in Figs. 7 and 8.

3.3. *On dimensional accuracy*

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 Figs. 9 and 10 for both the materials 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 (MFTW) system and thermal expansion of the job during machining followed by cooling. Therefore, if the MFTW 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.



(a) (b)

Fig. 8. Growth of average auxiliary flank wear, V_S with time in machining AISI E4340C steel under dry and cryogenic conditions by (a) SNMG and (b) SNMM inserts.

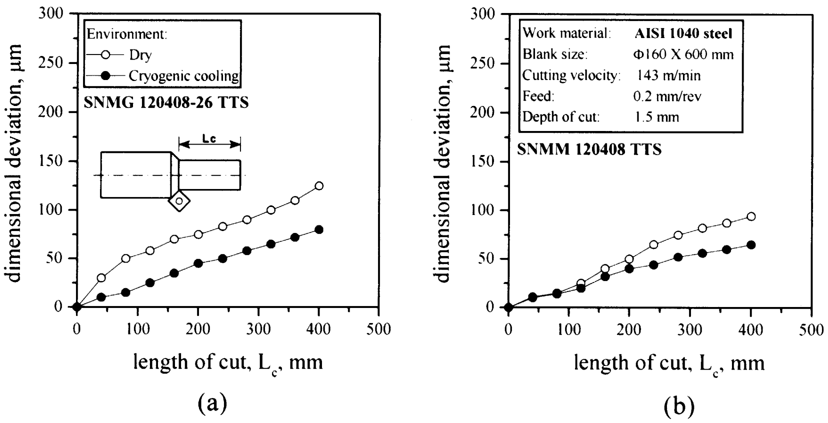


Fig. 9. Dimensional deviations after one full pass turning of the AISI 1040 steel rod by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions.

Cryogenic cooling resulted much lesser dimensional deviation particularly in case of machining the AISI E4340C steel as can be seen in Figs. 9 and 10. It is also to be noted in Figs. 5 and 8 that reduction in V_S by cryogenic cooling has also been relatively less in case of the AISI 1040 steel. The possible amount of dimensional deviation due to system compliance of the MFTW system and thermal expansion of the job, estimated based on the present job configuration, expected cutting forces and heat absorbed by the job, appears to be almost insignificant compared to the actual amount of deviation observed. Therefore, the cause of the dimensional deviations may be attributed mainly to auxiliary flank wear. The factors, which play major role on V_S under both dry and cryogenic machining, are reasonably expected to play similar role on dimensional accuracy also. Fig. 10 clearly shows that in case of AISI E4340C steel the growth of dimensional inaccuracy drastically decreased due to cryogenic cooling. The degree of such improvement has been even higher than that in V_S (Fig. 8) possibly for increase in V_c from 103 m/min, taken for wear tests, to 130 m/min, taken for accuracy tests.

3.4. On surface finish

Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economise the grinding operation and reduce initial surface defects as far as possible.

Surface roughness for each treatment was also measured at regular intervals while carrying out machining for tool wear study. It was found that surface roughness grew substantially, though in different degree under different tool–work-environment combinations, with the progress of machining. Comparison of Figs. 11 and 12 with Figs. 5 and 8

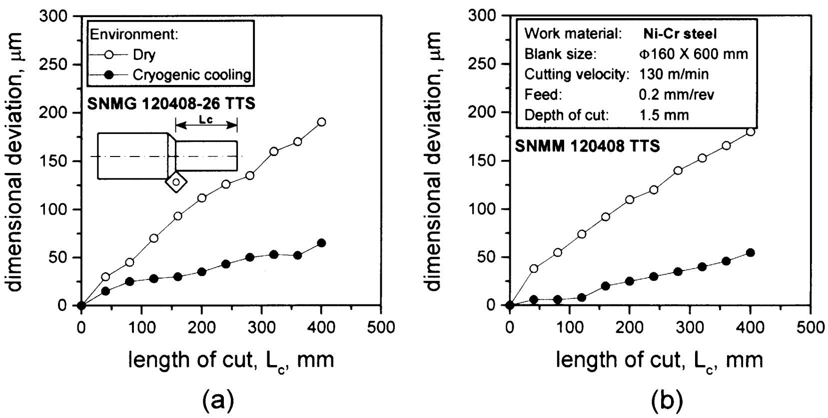
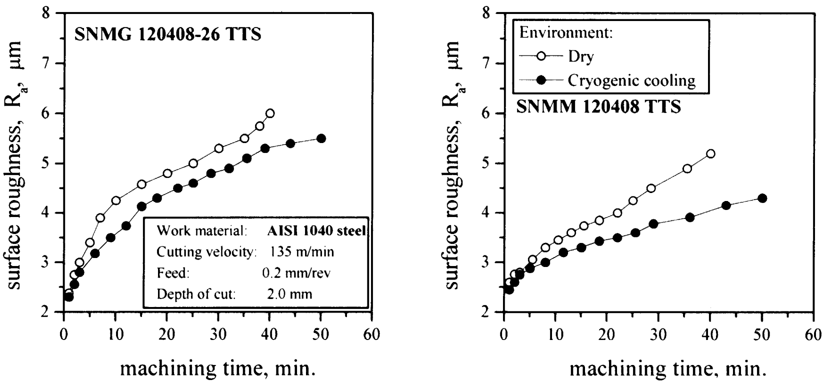
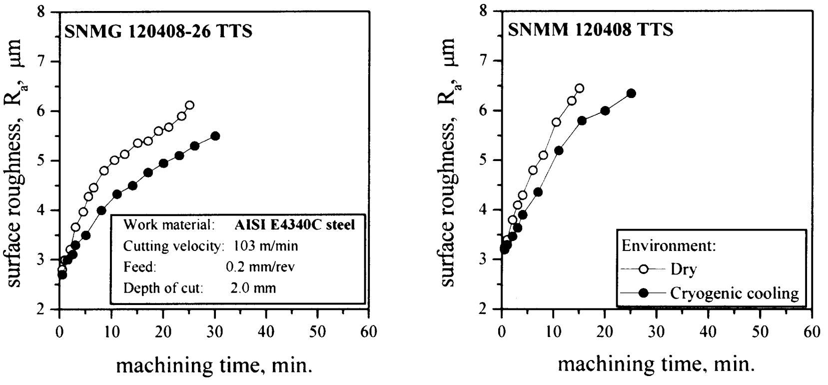


Fig. 10. Dimensional deviations observed after turning AISI E4340C steel rod by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions.



(a) (b)

Fig. 11. Surface roughness developed with progress of machining of the AISI 1040 steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions.



(a) (b)

Fig. 12. Surface roughness developed with progress of machining of the AISI E4340C steel by (a) SNMG and (b) SNMM inserts under dry and cryogenic conditions.

reveals that the pattern of growth of surface roughness also bears similarity with that of growth of auxiliary flank wear, V_S in particular. This has been more or less true for all the tool–work–environment combinations undertaken. Such observations indicate distinct correlation between auxiliary flank wear and surface roughness also like dimensional deviation. Wear at the tool flank is caused mainly by microchipping and abrasion unlike crater wear where adhesive and diffusion wear are predominant particularly in machining steels by uncoated carbides. The minute grooves produced by abrasion and chipping roughen the auxiliary cutting edge at the tool-tip, which is directly reflected on the finished surface. Deep notching, if develops at the tool-tip, would enhance surface roughness. Built-up edge formation also is likely to affect surface finish directly being stuck to the cutting edge as well as finished surface and indirectly by causing chipping and flaking at the tool tip.

It appears from Fig. 11 that in machining AISI 1040 steel, surface roughness grows quite fast under dry machining. But cryogenic cooling could not provide that significant improvement as was noted in case of V_S (Fig. 5). In case of AISI E4340C steel, which as such produced higher surface roughness under dry machining expectedly due to more intensive temperature and stresses at the tool-tips, cryogenic cooling appeared to be more effective in reducing surface roughness (Fig. 12) as it did for auxiliary flank wear. However, it is evident that cryogenic cooling by liquid nitrogen jets substantially improves surface finish depending upon the work–tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

4. Conclusions

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

1. Application of cryogenic cooling by liquid nitrogen jets can provide not only environment friendliness but also substantial technological benefits as has been observed in machining some steels by carbide tools.

2. The present cryogenic cooling systems enabled reduction in average chip–tool interface temperature upto 34% depending upon the work materials, tool geometry and cutting conditions and even such small reduction enabled significant improvement in the major machinability indices.
3. The most significant contribution of application of liquid nitrogen jets in machining the steels by the carbide inserts undertaken has been the high reduction in flank wear, which would enable remarkable improvement in tool life. Such reduction in tool wear might have been possible for retardation of abrasion and notching, decrease or prevention of adhesion and diffusion type thermal sensitive wear at the flanks and reduction of built-up edge formation which accelerates wear at the cutting edges by chipping and flaking. Deep notching and grooving, which are very detrimental and may cause premature and catastrophic failure of the cutting tools, are remarkably reduced by cryogenic cooling.
4. Dimensional accuracy and surface finish also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of liquid nitrogen.
5. The geometry of cutting tools played significant role on the degree of improvement in machinability of the steels by cryogenic application which becomes more effective when the tool geometry allows more intensive cooling of the chip–tool interface and the tool flanks.
6. Cryogenic cooling, if properly employed, can provide, besides environment friendliness, significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cryogenic cooling system and cryogen.

Acknowledgements

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