Study of Environmentally Conscious Cryogenic Cooling Machining

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Abstract: In machining, a cutting tool is used to remove workpiece material to precise geometry, tolerance and finish. Cutting friction generates significant heat which shortens tool life. Current processes use synthetic oil based cutting fluids for cooling. These fluids are environmentally hazardous and disposing of them is increasingly regulated and costly. Metal chips generated on a machining by product are considered hazardous because of cutting fluid contamination and are generally land filled. Moreover, prolonged worker contact with cutting fluids may cause severe dermatitis.

Cryogenic machining is a promising new technology which economically addresses the current processes' environmental and health concerns. This process injects liquid nitrogen (-196°C) through a macro-nozzle at the precise location required to cool the tool and the immediate cutting zone. Chilling the cutting tool by liquid nitrogen jets enhances tool hardness and life, dimensional accuracy and improves surface roughness. Cooling the chip makes it brittle and aids removal. Because nitrogen is an abundant atmospheric constituent and the quantities used are small, there is no unfavorable environmental or health impact nor coolant disposal cost and the chips are readily recycled.

Key words: *Machining, Liquid nitrogen, Cutting forces, Tool wear, Product quality*

INTRODUCTION

Science and Technology are growing fast, particularly due to liberalization and global cost competitiveness to meet the growing demand for higher productivity, product quality and overall economy. Another requirement in manufacturing industries has been the control of environmental pollution, which has become a great concern of the modern society. The pollution created in manufacturing not only affects the performances and health of the workers but also the surroundings.

Performances and the service life of the engineering products of given material depends upon their dimensional and form accuracy and surface quality. The preformed blanks are generally semi-finished and finished by machining and grinding. But improvement in productivity as well as precision by increasing speed and feed are restrained by development of high cutting temperature, particularly in case of strong, hard and sticky work materials, which not only reduces life of the tools but also causes dimensional inaccuracy and impairs the surface integrity of the products by rapid oxidation and corrosion and inducing harmful tensile residual stress and micro cracks of the surfaces and subsurfaces [1].

Such high cutting temperatures generally tried to be reduced by application of cutting fluids in addition to proper selection of the process parameters and tools depending upon the work materials. But conventional application of cutting fluid is found to be almost ineffective when the cutting temperature is very high due to machining and grinding at high speeds and feeds, when the work materials are difficult to machine and grind for their high strength and high resistance [2,3]. Besides that, application of conventional cutting fluids, generally oil base, causes severe environmental pollution and inconveniences. The major socio-economic problems that due to such use of cutting fluids are [4-7] :

(i) wetting and dirtiness of the working zone
(ii) possible damage of the machine tools by corrosion and mixing of the cutting fluid into harmful gases
(iii) biological hazards to the operators from bacterial growth in the cutting fluids [8]
(iv) requirement of additional systems for local storage, pumping, filtration, recycling, recording, large spaces and disposal of the used up fluids which further causes soil contamination and water pollution in the vicinity.

Attempts have been made[9] to reduce or overcome such problems by conducting machining under dry condition using sophisticated tools like high performance ceramics, cubic boron nitride and diamond tools which are extremely heat and wear resistive. But their success was limited. Very recently a unique technique has been developed where cryogen is used as the coolant. Extensive research is going on in this direction. Cryogenic cooling by agents like liquid nitrogen provides not only desired cooling but also environment friendliness[10,11]. Such cryogenic cooling provides dry, neat and cool environment during machining and grinding without any disposal problems. But the industries would also obviously look into the techno-economic aspects even of such novel environment friendly technique for feasibility and economical viability.

The present work briefly deals with the method of application of cryogenic cooling and the observations made so far on the effects of such new technique on cutting forces, tool life and product quality, which govern the overall economy in machining.

EXPERIMENTAL INVESTIGATIONS - PROCEDURE

Liquid nitrogen drawn from a self-pressurized dewar (XL-45, USA) was impinged in the form of two thin but high speed jets through a specially developed nozzle towards the cutting zone. Two high carbon steels (C-40 steel and C-60 steel) and two alloy steels (Ni-Cr steel and 17CrNiMo6 steel) of varying strength and hardness were machined in a heavy duty center lathe (11kW: NH22 HMT, India) by P30 carbide inserts of two different geometry (SNMG 120408-26 and SNMM 120408) at different cutting velocity (V_c) and feed (S_o) under both dry and cryogenic cooling condition. Only the C-60 steel was machined also with soluble oil to demonstrate the ineffective/detrimental role of conventional cutting fluid application in high production machining of steels by carbides. The experimental setup is schematically shown in Figure 1.

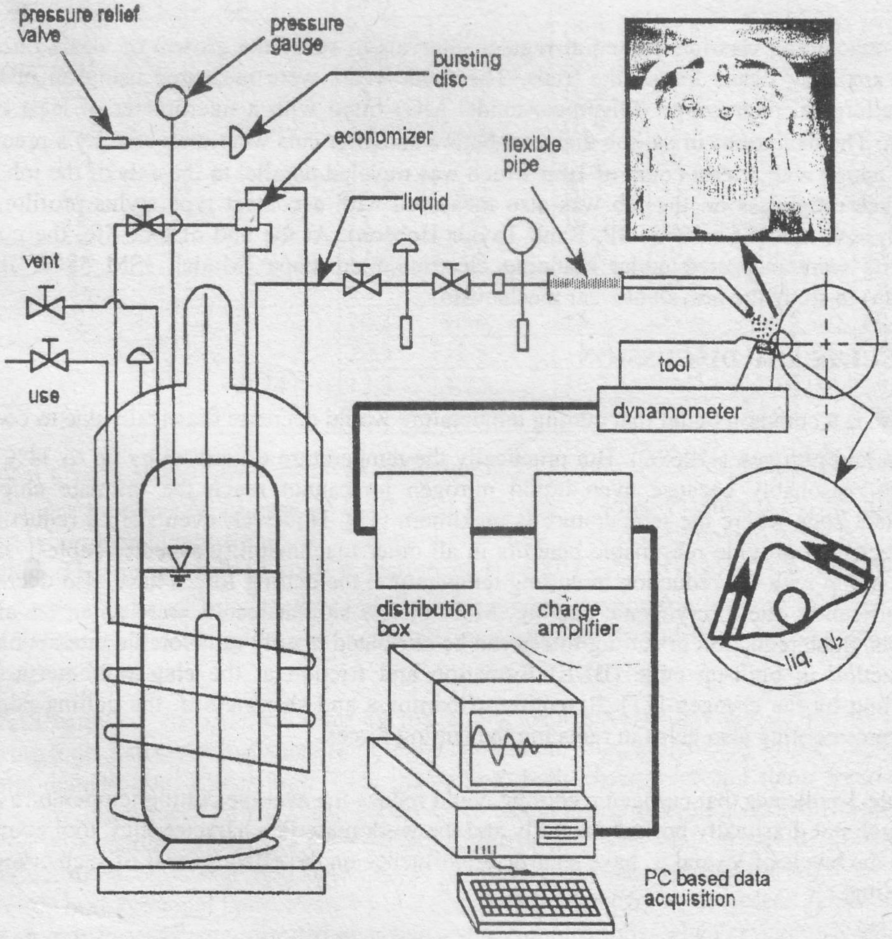


Figure 1: Schematic layout of experimental set-up.

Application of liquid nitrogen is expected to affect the various machinability characteristics mainly by reducing the cutting temperature. The average cutting temperature was measured by simple but reliable tool-work thermocouple technique with proper calibration. The temperature could be measured smoothly under dry machining condition but some problems like wide scatter in the temperature readings were found to occur under cryogenic cooling. So the average cutting temperature under cryogenic cooling was evaluated using validated thermal modeling of machining [12].

The cutting forces components, P_z (tangential or main component) and P_x (axial component) were monitored by a 3-D dynamometer (KISTLER, 3D-dynamometer, Model: 3 component dynamometer, Type: 9257B; and Charge Amplifier: 5007) and recorded in a PC through a data acquisition system (Dasylab-Full win 95 version, PCL 818 HG 12 bit highgain multifunction DAS card and Sampling frequency 2000 Hz).

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 an inverted metallurgical microscope (Olympus: model MG) fitted with a micrometer of least count 1μm. The deviations in the job diameter before and after cuts were measured by a precision dial gauge with a least count of 1μm which was traveled parallel to the axis of the job. The surface roughness on the job was also measured with a contact type stylus profilometer (Talysurf: model Surtronic 3P, Rank Taylor Hobson). At the end of tool life, the cutting inserts were inspected under scanning electron microscope (Model: JSM 5800, JEOL, Japan) to study the prevalent wear mechanism.

RESULTS AND DISCUSSION

There is a common belief that cutting temperature would decrease drastically due to cooling by liquid nitrogen (-196^{o}C). But practically the temperature decreased by up to 34% only quite reasonably because even liquid nitrogen jet cannot reach the intimate chip-tool contact zone where the temperature is maximum [12]. However, even such a reduction is expected to provide reasonable benefits in all other machinability aspects. Table-1 shows that along with the reduction in cutting temperature, the cutting forces have also decreased significantly due to cryogenic cooling. More or less similar results were noted for all the steels. Such reduction in cutting forces can be attributed mainly to favorable interaction like reduction in built-up edge (BUE) formation and friction at the chip-tool interface for cooling by the cryogen [11]. Retention of hardness and sharpness of the cutting edge by extreme cooling also helps in reducing the cutting forces.

Table-1 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_o have significant influence on the effectiveness of such cryogenic cooling.

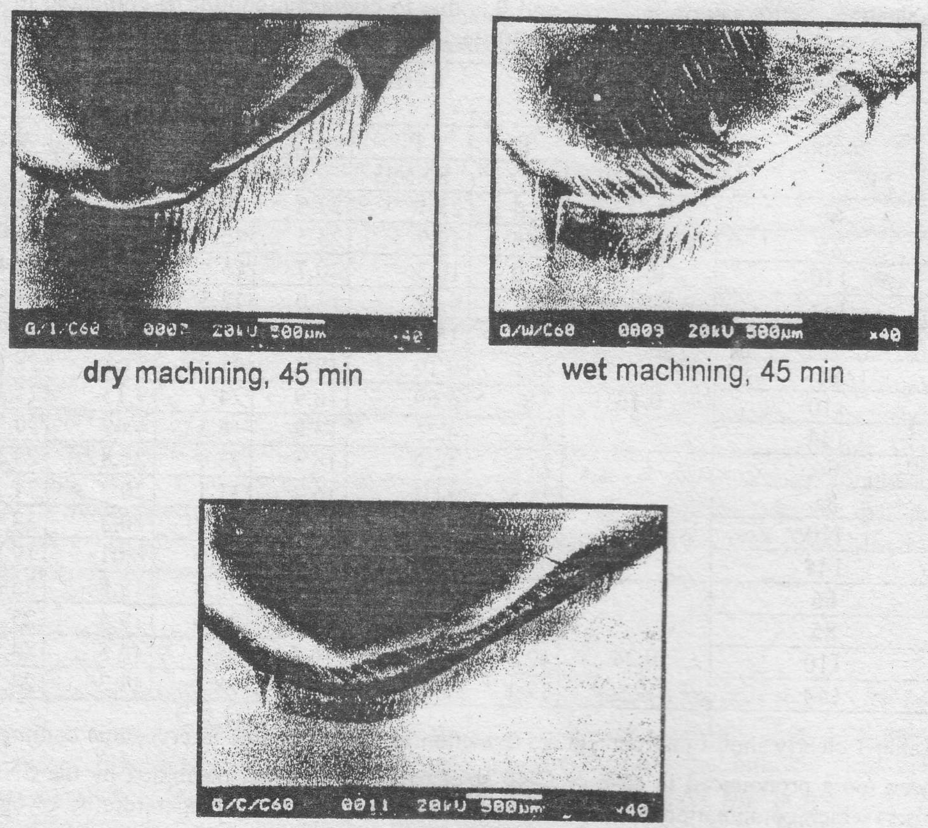
Both the cutting force components, P_Z and P_X more or less decreased under different conditions with the increase in V_c, as usual, due to plasticization and shrinkage of the shear zone and reduced friction at the chip-tool interface and increased with increase in S_o simply for increase in chip load. Cryogenic cooling enabled reduce both P_Z and P_X, though in different percentage, under different V_c-S_o combinations and for different tool-work combinations.

Table-1 Reduction in forces and θ_{avg} due to cryogenic cooling is compared to dry machining in turning C-40 steel by SNMG and SNMM inserts.

Cutting velocity, V_c m/min	Feed rate, S_o rev/min	Percentage reduction in					
		P_x	P_z	θ_{avg}	P_x	P_z	θ_{avg}
		SNMG			SNMM		
66	0.12	38.4	23.1	27.5	54.8	31.6	33.9
85		34.5	19.7	25.5	42.7	22.6	30.9
110		18.0	10.3	20.7	15.9	9.36	21.4
144		7.6	6.52	15.0	12.5	2.8	18.8
66	0.16	22.0	15.3	19.3	54.4	33.4	33.3
85		19.0	9.19	19.4	41.0	21.8	28.8
110		7.8	6.69	16.9	24.1	9.15	21.3
144		9.3	4.26	13.8	16.3	4.67	20.3
66	0.20	23.2	14.9	16.5	33.9	21.8	27.2
85		23.5	11.3	16.2	31.1	20.2	24.3
110		12.6	2.65	15.0	19.9	10.3	23.4
144		6.3	2.1	14.5	16.0	6.01	19.8
66	0.24	20.3	10.6	15.7	32.0	18.8	25.0
85		20.3	12.8	16.9	31.8	19.4	25.7
110		12.3	4.73	16.7	26.5	16.8	24.2
144		12.1	2.17	15.4	18.1	11.3	24.3

Table-1 clearly shows that percentage reduction in P_Z and P_X due to cryogenic cooling has been more pronounced in case of C-40 steel particularly when machined by the SNMM insert which combination showed maximum reduction in cutting temperature by cryogenic cooling. The reason behind such reduction in P_Z and P_X by cryogenic cooling may be reasonably attributed to reduction in chip-tool contact length, friction and built-up edge (BUE) formation due to reduction in cutting zone temperature and favorable change in the chip-tool interaction.

Overall economy in manufacturing by machining depends significantly on the tool life. Cutting tools like carbides generally fail by wear and only occasionally by brittle fracture or plastic deformation. Under high V_c-S_o machining, both crater wear and flank wear occur almost by same mechanism. Most of the wear mechanisms like adhesion, diffusion and plastic deformation are temperature sensitive. Therefore, wear and its rate of growth are expected to decrease if temperature can be controlled. It was observed during the present tests that both principal flank wear, V_B and auxiliary flank wear, V_S decreased substantially, though in different degree for different tool-work combinations, when cryogenic cooling is employed. Therefore, cryogenic cooling, if properly employed, would improve tool life significantly. Fig.2 typically shows how cryogenic cooling enabled substantial reduction in tool wear unlike soluble oil which did not help at all. It is evident from Fig.3 that for value of wear as 300 μm, the tool life can increase by 100 to 200% by cryogenic cooling which retarded damage and wear of the cutting edges usually caused by temperature intensive wear like adhesion and diffusion and also by built-up edge formation.



dry machining, 45 min

wet machining, 45 min

cryo machining, 50 min

V_c = 110 m/min, S_o = 0.20 mm/rev, t = 2.0 mm

Figure 2: SEM views of the worn out SNMG insert after machining C-60 steel under dry, wet and cryogenic cooling condition.

Quality of a machined product, which governs its performance and service life depends mainly upon the material, dimensional accuracy and surface integrity of the product. The heat and the cutting temperature generated during machining, if very high and not controlled, may cause dimensional and form inaccuracy due to thermal distortion as well as consecutive thermal expansion and cooling after machining. Bulk cooling and reduction of the localized cutting zone temperature by cryogenic application has enabled in the present cases substantial reduction (more than 80%) in the variation in diameter along the length of the machined jobs. Retention of sharpness of the auxiliary cutting edge near the tool tip by cryogenic application enables substantial reduction in dimensional deviation as can be seen typically in Fig.4.

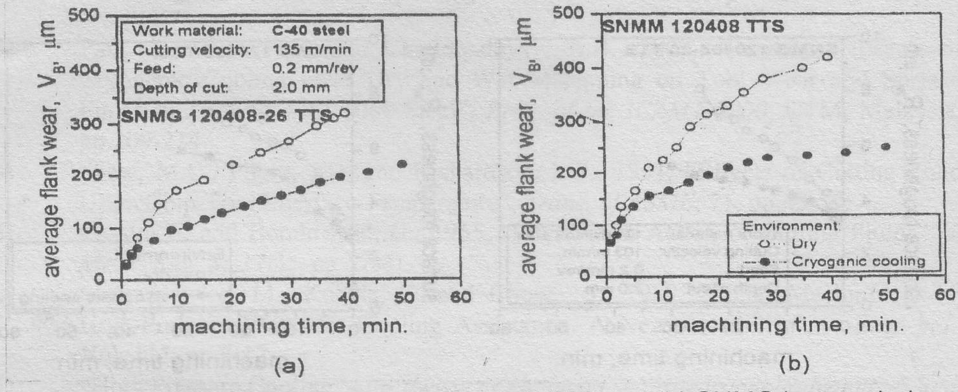


Figure 3: Growth of flank wear, V_s in (a) SNMG and (b) SNMG inserts during machining C-40 steel at V_c 135 m/min under dry and cryogenic condition.

Surface integrity generally covers both visible surface topography (roughness) and the apparently invisible aspects like residual stresses and surface and subsurface micro cracks. Surface roughness in turning is mainly caused by the feed marks and this inherent roughness depends upon the value of feed and the tool geometry, particularly the nose radius and the auxiliary cutting edge angle. The surface condition gets further degraded by the nature and extent of the wear at the nose and auxiliary flank of the cutting inserts. The improvement in surface finish attained by cryogenic cooling may be attributed to reduction in damage and wear of the tool nose and auxiliary flank through retention of the tool hardness and control of adhesion and diffusion. Cryogenic application also enabled significant reduction in surface roughness, as can be seen in Fig.5, quite expectedly for reduction in chipping, abrasion and notching wear at the tool tip and built-up edge formation.

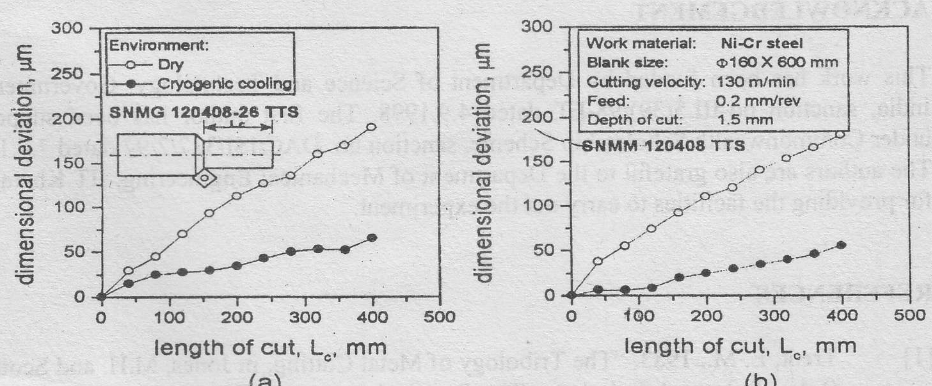


Figure 4: Dimensional derivatives observed after one full pass turning of the Ni-Cr Steel by (a) SNMG and (b) SNMG inserts under dry and cryogenic conditions.

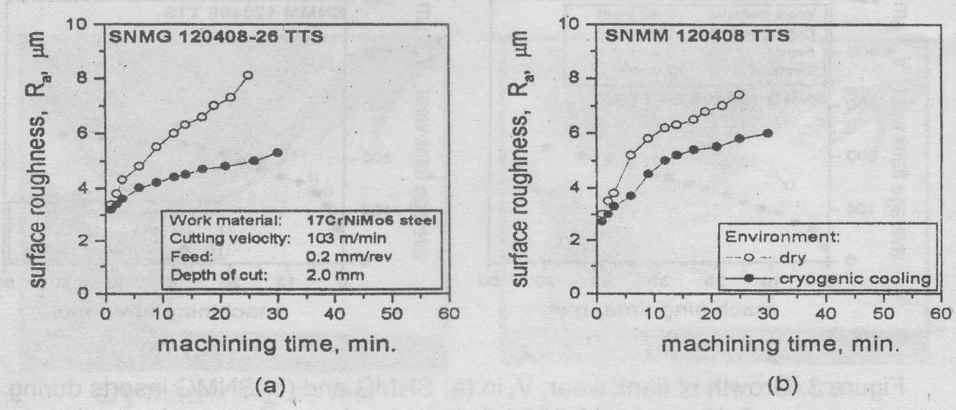


Figure 5: Surface roughness developed with progress of machining of the 17CrNiMo6 Steel by (a) SNMG and (b) SNMG inserts under dry and cryogenic conditions.

CONCLUSIONS

1. Proper application of cryogenic cooling not only provides environment friendliness but also lot of techno-economical benefits.
2. Cryogenic cooling in machining steels by carbide inserts resulted substantial saving in energy consumption, enhancement of tool life and improvement in product quality mainly through reducing cutting forces, tool wear and friction at the chip tool interface.
3. The degree of benefits of cryogenic application in machining varies with the work tool materials and geometry and also the levels of process parameters.

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