VOL.1, NO.1, JUNE 2006 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Effect of Cryogenic Cooling by Liquid Nitrogen Jet on Tool Wear and Product Quality in Turning AISI-9310 Steel

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ABSTRACT

Growing demand for higher material removal rate (MRR) in machining necessitated much increase in cutting velocity, which eventually required the efficiency of cooling to be increased in order to cope with the increase in the cutting temperature. Cryogenic cooling by liquid nitrogen jet is a promising new technology in high production machining which economically addressed the current process environmental and health concern. High production and finish machining are inherently associated with generation of intense heat and cutting temperature at the cutting zone. Such high cutting temperature not only reduces tool life but also impairs the surface integrity of the job. So the temperature at the cutting tool interface is one of the important factors influencing the machining process while primarily dependent on the cutting speed and the work piece material properties as well as cutting tool performance. The present paper 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 9310 steel by coated carbide insert (SNMG). The results have been compared with dry machining. The results of the present work indicate substantial reduction in tool wear, which enhanced the tool life, dimensional accuracy and surface finish. This may be mainly attributed to reduction in cutting zone temperature and favorable change in the chip-tool interaction.

Keywords: Cryogenic cooling, temperature, tool wear, dimensional accuracy and surface finish.

INTRODUCTION

Any manufacturing process for its fruitful implementation essentially needs to be technologically acceptable, technically feasible and economically viable. The fourth dimension that has been a great concern of the modern industries and society is environment-friendliness in and around the manufacturing shops. The performance and service life of engineering component depends on their material, dimensional and form accuracy and surface quality. Machining and grinding to attain the desired accuracy and surface integrity finish the preformed blanks.

The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, particularly to meet the challenges thrown by liberalization and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools. But high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but 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 (Leskover and Grum, 1986; Tonshoff and Brinkomeier, 1986).

Use of cutting fluids was always considered a solution rather than a problem in machining, at least till recently. They serve many useful functions (Shaw, Pigott and Richardson, 1951; Merchant, 1958; Cassin and Boothroyed, 1965), including, cooling of the cutting tool at higher speeds, lubrication at low speeds and high loads, increasing tool life, improve the surface finish, reducing the distortion due to temperature rise in the workpiece, chip handling and disposal, providing a protective layer on the machined surface from oxidation and protection of the machine tool components from rust. For a long time, because of the limitations on the tool materials available, the use of cutting fluid was considered as an essential integral part of the machine tool system. All the ill effects associated with the use of cutting fluids were considered as a price for improving productivity. Various methods were developed to minimize their adverse effects although progress was far less than desired. The detrimental effects of the cutting fluids include the cost of the cutting fluid system (Aronson, 1995), i.e. the fluid itself, pumping systems, collection and filtering system, storage and disposal, and sometimes a re-circulating system etc; the physiological effects on the operator, namely, toxic vapors, unpleasant odors, smoke fumes, skin irritations (dermatitis) (Welter, 1978; Bennett, 1983; Thony, Thony, Lafontaine and Limasset, 1975), or effects from bacteria cultures from the cutting fluid; and its overall effect on the worker safety and on the environment. In some applications the consumption of cutting fluids has been reduced drastically by using mist lubrication. However, mist in the industrial environment can have a serious respiratory effect on the operator (Kennedy, 1989; Bennett and Bennett, 1985). Consequently, high standards are being set to minimize this effect. Use of cutting fluid will become more expensive as these standards are implemented leaving no alternative but to consider cryogenic machining.

Application of cryogen for effective cooling without polluting the environment is becoming more and more popular (Dhar, Kamruzzaman, Khan and Chattopadhyay, 2006; Dhar, Kamruzzaman, Islam and Paul, 2006; Dhar, Paul and Chattopadhyay, 2002; Ding and Hong, 1998; Wang and Rajurkar, 1997; Wang, Rajurkar and Murugappan, 1996; Hong, Qu and Lee, 2001). 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 temperature, 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.

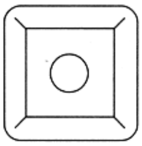
The objective of the present work was to experimentally investigate the role of cryogenic cooling by liquid nitrogen (-196°C) jet on tool wear, surface finish and dimensional accuracy of the product in machining of AISI-9310 steel by coated carbide insert (SNMG) under dry and cryogenic cooling conditions.

EXPERIMENTAL CONDITIONS AND PROCEDURE

The beneficial role of cryogenic cooling by agent like liquid nitrogen on environment friendliness has already been established. The aim of the present work is primarily to explore and evaluate the role of such cryogenic cooling on machinability characteristics of AISI-9310 steel and coated carbide insert (SNMG) combination mainly in terms of cutting temperature, tool life and surface finish which govern productivity, product quality and overall economy.

Liquid nitrogen drawn from a self-pressurized dewar (USA) was impinged in the form of thin but high-speed jet through a nozzle towards the cutting zone. The machining tests have been carried out by straight turning of steel (AISI-9310 steel) in a lathe machine (Lathe Machine, France, 4 hp) by standard coated carbide insert (SNMG) at different cutting velocities (V_c) and feeds (S_o) under dry and cryogenic cooling conditions. The experimental conditions under which the machining tests have been carried out are briefly given in Table-1. The cutting velocity (V_c) and feed rate (S_o) have been selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed to only 1.0 mm, which would adequately serve the present purpose.

Table-1. Experimental conditions

Machine tool	Lathe Machine (France), 4 hp
Work specimens	
Materials	AISI 9310 steel (C-0.12%, Mn-0.55%, P-0.025%, Si-0.25%, Ni-3.4%, S-0.025%, Cr-1.3%, Mo- 0.14%)
Hardness (BHN)	257
Size	Φ125 X 650 mm
Cutting insert	Coated carbide, Sandvik Coating: TiCN + Al_2O_3  **SNMG 120408-26**
Tool holder	PSBNR 2525 M12 (ISO specification), Sandvik
Working tool geometry	Inclination angle : -6° Orthogonal rake angle : -6° Orthogonal clearance angle : 6° Auxiliary cutting edge angle : 15° Principal cutting edge angle : 75° Nose radius : 0. 8 mm
Process parameters	
Cutting velocity, V_c	348 m/min
Feed rate, S_o	0.13 mm/rev
Depth of cut, t	1.0 mm
Environment	Dry and cryogenic cooling by liquid nitrogen

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangements made and used have been shown in Fig.1 (top right). The jet is projected parallel to the auxiliary cutting edge mainly to cool the chip-tool interface and the auxiliary flank. The photographic view of the experimental set-up is shown in Figure-1.

Application of liquid nitrogen is expected to affect the various machinability characteristics mainly by reducing the cutting temperature. Simple but reliable tool-work thermocouple technique with proper calibration was used to measure the average cutting temperature (Dhar, Paul and Chattopadhyay, 2002).

The machining was interrupted at regular intervals to study the growth of wears on principal and auxiliary flanks for all the trials. The flank wears ($V_{B,}$ V_M, V_N $V_{S,}$ etc.) 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 (Phillips New XL-30, Netherlands) 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.

Figure-1a. Photographic view of the experimental set-up

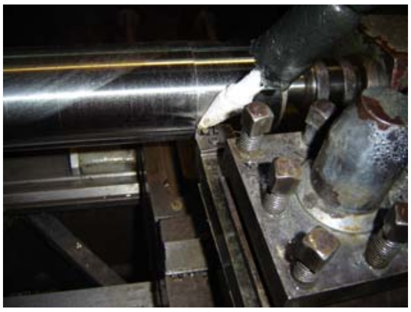


Figure-1b. Photographic view of the experimental set-up. Nozzle injecting liquid nitrogen.

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 by about 10 to 15% 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 Figure-2.

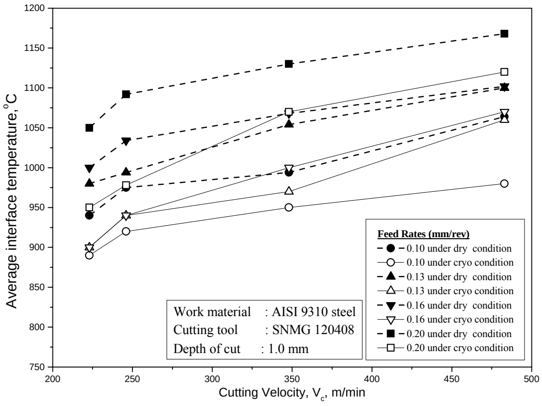


Figure-2. Variation in average interface temperature with that of V_c and S_o under dry and cryogenic cooling conditions.

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. 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 Figure-3 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 of 0.3 mm (Ezugwu et al. 2005). 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.

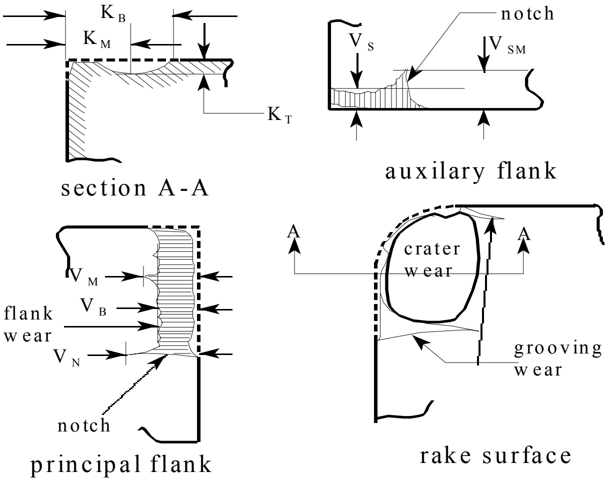


Figure-3. Geometry and major features of wear of turning tools.

Figure-4 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.

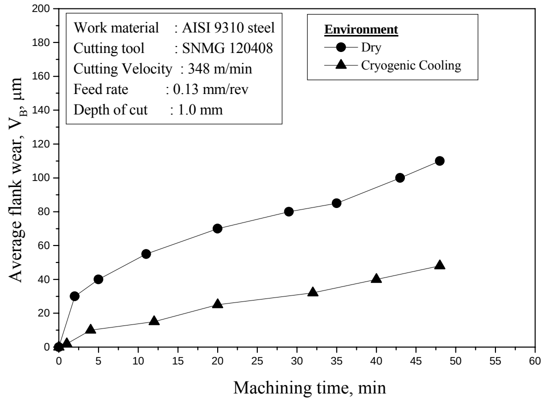


Figure-4. Growth of average flank wear, V_B with time in machining steel under dry and cryogenic cooling conditions at cutting velocity 348 m/min.

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.5 that auxiliary flank wear (V_S) has also decreased remarkable due to proper temperature control under cryogenic cooling.

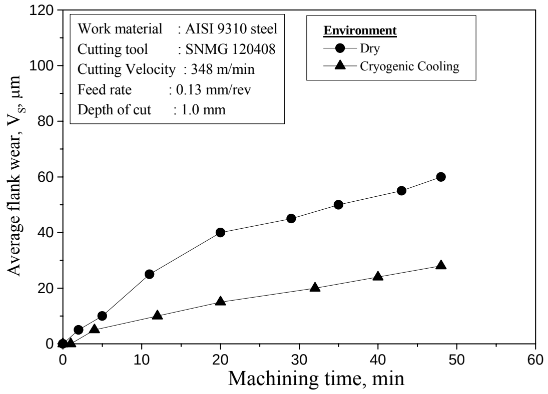


Figure-5. Growth of auxiliary flank wear, V_S with time in machining steel under dry and cryogenic cooling conditions at cutting velocity 348 m/min.

Figures-6a and b show the SEM photographs of worn out insert used for machining steel bar for 50 minutes under dry and cryogenic environments. The main cutting edge of the insert was found to suffer from chipping and flaking seemingly due to formation of built up edge under dry condition. No notch and groove wear were observed under cryogenic cooling condition due to chemical inertness of alumina and TiCN. The coating allowed less crater wear under all cryogenic condition as it acts as good thermal and diffusion barrier. Cryogenic cooling expectedly reduced main flank and auxiliary flank wear.

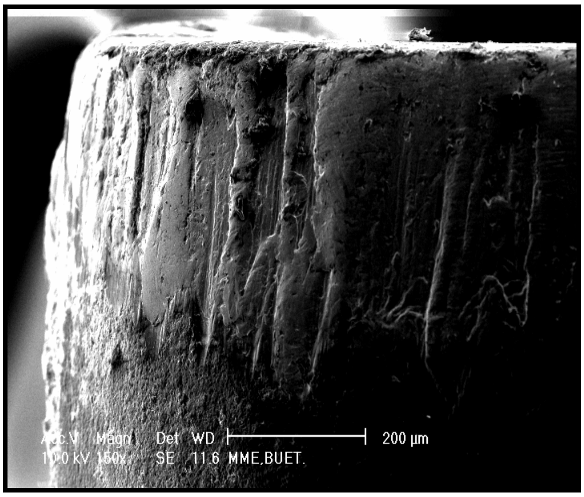


Figure-6a. SEM view of principal flank wear of the worn out insert after machining 50 minutes under **dry** machining conditions.

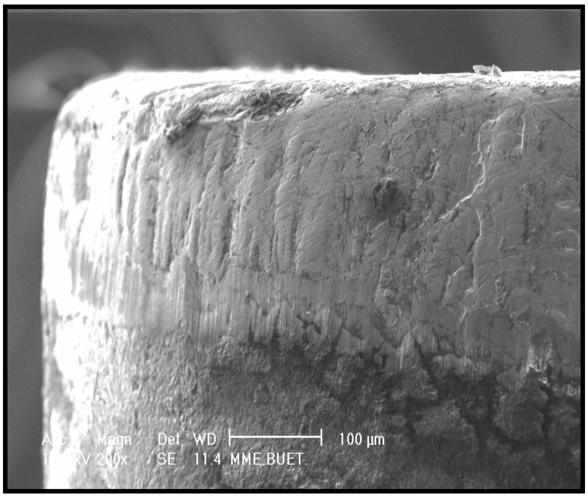


Figure-6b. SEM view of principal flank wear of the worn out insert after machining 50 minutes under **cryogenic** machining conditions.

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 Vc. Built-up edge formation and vibration worsen the surface further. Surface roughness gradually increased as usual with the machining time as can be seen in Fig.7 due to gradual increase in auxiliary flank wear (VS). Again it was observed that the rate of increase in surface roughness decreased to some extent when machining was done under cryogenic cooling which not only reduced the VS but also possibly built-up edge formation due to reduction in temperature.

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.

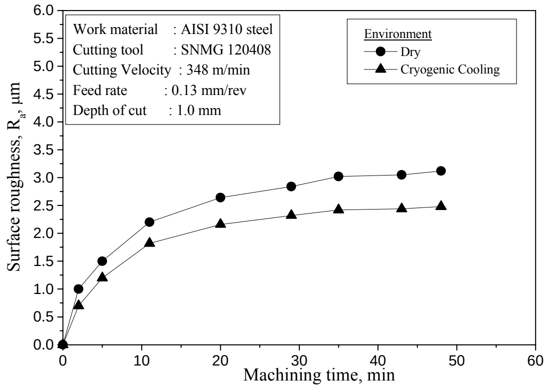


Figure-7. Surface roughness developed with progress of machining under dry and cryogenic conditions

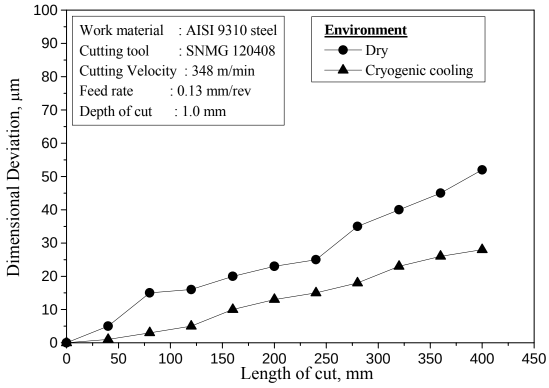


Figure-8. Dimensional deviations observed after one full pass turning at cutting velocity, 348 m/min under dry and cryogenic conditions.

CONCLUSION

- 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. 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. Cryogenic cooling by liquid nitrogen jet provided lesser tool wear, better surface finish and higher dimensional accuracy as compared to dry machining.
- Cryogenic cooling, if properly employed, can enable 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.

ACKNOWLEDGEMENT

This research work was funded by Directorate of Advisory Extension and Research Services (DAERS), BUET, Dhaka, Bangladesh. The authors are also grateful to the Department of Industrial and Production Engineering, BUET, Dhaka for providing the facilities to carryout the experiment. The help extended by the Department of Materials and Metallurgical Engineering, BUET, Bangladesh for obtaining the scanning electron micrograph is also sincerely acknowledged.

REFERENCES

Aronson, R. B. 1995. Why Dry Machining. Manufacturing Engineering. Vol. 114, pp. 33-36

Bennett, E. O. 1983. Water Based Cutting Fluids and Human Health. Tribology Int.

Bennett, E. O. and Bennett, D. L. 1985. Occupational airway diseases in the metal-working industry. Tribology Int. Vol. 18(3), pp. 169-176

Cassin, C. and Boothroyed, G. 1965. Lubrication action of cutting fluids. Journal of Mech. Eng. Science, Vol. 17(1), pp. 67-81

Dhar, N. R., Kamruzzaman, M., Islam, S and Paul, S. 2006. Wear Behavior of Uncoated Carbide Inserts under Dry, Wet and Cryogenic Cooling Conditions in Turning C-60 Steel. Journal of the Brazilian Society of Mechanical Sciences. [in press]

Dhar, N. R., Kamruzzaman, M., Khan, M. M. A. and Chattopadhyay, A. B. 2006. Effects of Cryogenic Cooling by Liquid Nitrogen Jets on Tool Wear, Surface Finish and Dimensional Deviation in Turning Different Steels. International Journal of Machining and Machinability of Materials (IJMMM), 2006. [in press]

Dhar, N. R., Paul, S. and Chattopadhyay, A. B. 2002. Machining of AISI 4140 steel under cryogenic cooling-tool wear, surface roughness and dimensional deviation. Journal of Materials Processing Tech. Vol. 123, pp. 483-489

Ding, Y. and Hong, S. Y. 1998. Improvement of chip breaking in machining low carbon steel by cryogenically precooling the workpiece. Trans. of ASME, Vol. 120, pp. 76-83

Ezugwu, E.O., Da Silva, R.B., Bonney, J. and Machado, A.R.. 2005. Evaluation of Performance of CBN Tools When Turning Ti-6Al-4V Alloy with High Pressure Coolant Supplies. International Journal of Machine Tools and Manufacture. Vol. 45, pp. 1009-1014.

Hong, S., Qu, X. and Lee, A. 2001. Economical cryogenic milling for environmentally safe manufacturing. Technical Papers of the North American Manufacturing. Home Page: http://www.columbia.edu/~ahl21/index2.html

Kennedy, S. M. 1989. Acute pulmonary responses among automobile workings exposed to aerosols of machining fluids. American J. of Industrial Medicine. Vol. 15, pp. 627-641

Leskover, P. and Grum, J. 1986. The metallurgical aspect of machining. Annals of CIRP 35/1, pp. 537-550

Merchant, M. E. 1958. The physical chemistry of cutting fluid action. Am. Chem. Soc. Div. Petrol Chem. Preprint 3, No. 4A, pp.179-189

Shaw, M. C., Pigott, J. D. and Richardson, L. P. 1951. The effect of cutting fluid upon chip-tool interface temperature. Trans. of ASME, Vol. 71, pp.45-56

Thony, C., Thony, J., Lafontaine, M. and Limasset, J. C. 1975. Occurrence of polycyclic aromatic hydrocarbons in some cutting oils study of the corresponding risk. Arch. Mal. Prof. Med. Trav. Sec. Soc., Paris, Vol. 36, pp. 37-52

Tonshoff, H. K., Brinkomeier, E. 1986. Determination of the mechanical and thermal influences on machined surface by microhardness and residual stress analysis. Annals of CIRP, Vol. 29(2), pp.519-532

Wang, Z. Y. and Rajurkar, K. P. 1997. Wear of CBN tool in turning of silicon nitride with cryogenic cooling. Int. J. of Mach. Tools and Manuf., Vol. 37, pp. 319-326

Wang, Z. Y., Rajurkar, K. P. and Murugappan, M. 1996. Cryogenic PCBN turning of ceramic (Si_3N_4). Wear. Vol. 195, pp. 1-6

Welter, E. S. 1978. Manufacturing exposure to coolant-lubricants. J. of Occupied. Med. l.20, pp. 535-538