CRITICAL ANALYSIS OF CRYOGENIC COOLING SYSTEM DURING TURNING OPERATION

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Abstract- The growing demand for high productivity machining need use of high cutting velocity, feed rate and depth of cut which in turn the high material removal rate. Such machining of high strength and heat resistance materials inherently generate very large amount of heat and high cutting temperature, which not only reduces tool life but also impairs the product quality. Conventional cooling methods are not only ineffective but also deteriorate the working environment by producing harmful gases and smokes. In addition, for machining High Strength Steel (H_{11}), the long, continuous chips can scratch the finished surface, snarl and jam automatic machine tool, causing considerable downtime in production. To eliminate or to reduce the above-mentioned limitations, cryogenic cooling, using liquid nitrogen as the coolant, is getting more importance nowadays. Liquid nitrogen bring the chip temperature near the embrittlement temperature of the workpiece and chips are broken into small, discontinuous, fragmented and irregular shapes. It also helps to maintain tool's form stability and reduce the magnitude of tool wear. Theoretical approach is also applied to investigate the temperature distribution in the cutting zone under both the dry and cryogenic environment. In the present research an attempt has also been made to analyze the wear of some tool inserts of tungsten carbide under Scanning Electron Microscope for both the dry and cryogenic condition for searching out the influence of cryogenic cooling on tool wear.

Key Words: Cryogenic Cooling, High Strength Steel, Tungsten Carbide, Tool Wear.

INTRODUCTION

Problems with Conventional Cooling

High production machining particularly of high strength and heat resistance materials, ceramics and MMC is associated with generation of large amount of heat and high cutting temperature which 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 of the tool material [1, 2]. It also causes dimensional deviation and premature failure of cutting tools due to form instability at elevated temperature and plastic deformation. The temperature up to which carbide tool maintains its form stability is about 1000^0C [3]. The extremely high tool wear rate and surface damage of workpiece produced during machining are mainly due to the high cutting temperature and the high hardness of work material. Hot machining softens the work piece and hence reduces its hardness, thereby making the machining relatively easy, but it increases the temperature in the cutting zone, and as a result, the temperature-dependent wear on the tool increases rapidly [4]. For machining high strength steel technically known as hot die steel, a typical ductile material, long continuous chips often snarl and jam automatic turning machine creating considerable machine down time. The chips may scratch the finished surface and are too bulky for disposal. With the increase of cutting speed and the ductility of the work material chips leads to form into overly broken, well broken or poorly broken. Also, there are growing concerns about the environmental contamination of conventional cutting fluids/oils and the health issues of dermatitis common to machinist [5].

Advantage of Cryogenic Cooling System

The temperature in the cutting zone can be reduced by cryogenic cooling and the temperature dependent wear gets reduced significantly. Also surface finish was about six times better than the normal cutting [6]. Development of cryogenic machining technology, is earning new interest in the industry for its advantages of longer tool life, higher cutting speed, better productivity, and lower production cost than the conventional process [7]. Liquid nitrogen maintains the tool's hot-strength at its desirable range to resist tool wear by dropping maximum temperature from 1153^{0}C to 829^{0}C. So 28% reduction of temperature is observed for the same machining conditions [8]. The material removal is taking place by ideal shearing and less by the ploughing, sliding and rubbing. Application of liquid nitrogen for effective cooling without polluting the environment is becoming increasingly popular. Besides these, the industries also reasonably insist economic viability through technological benefits in terms of product quality, tool life and saving of power consumption. 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 where high cutting temperature is the major concern and optimize the cryogenic application to derive maximum benefits [9]. Cooling the work piece or flooding the general cutting area with liquid nitrogen produces a cooling effect on the shear plane and may result in an undesirable increase in cutting resistance due to the material's temperature-dependent shear strength. So, it is essential to apply liquid nitrogen in properly sealed jets only to a localized cutting area specially to the chip faces adjacent to the flank face of the tool insert instead of flooding the general cutting zone which also minimize the liquid nitrogen consumption. Chips also help to reduce cutting zone temperature by carrying out maximum amount of heat generated during turning [10].

DEVELOPMENT OF EXPERIMENTAL SET-UP

Experiments for turning operation are carried out with the help of a PL-4 Lathe. To reduce the chattering and vibration and for proper centering Tail Stock Centre is used in addition to a three-jaw chuck. Tool holder with the provision for tool insert fixing facility is mounted on the tool post of the Lathe. After carrying out all the machining experiments under dry environment, cryogenic cooling arrangement is attached on the machining set-up for studying the effect of cryogenic cooling on tool wear. The cryogenic system consists of cryogenic flask, liquid nitrogen as the cryogenic coolant, silica gel, glass kettle, compressor, stop cock, and insulated vacuum pipeline, etc. Compressed air from the compressor entered into silica gel kettle for drying up the moisture content of the air and entered into the cryogenic flask and ultimately it forced the liquid nitrogen to flow through the exit tube and stop cock and finally it will be freed on to the chip faces adjacent to the insert's face. This vacuum insulated flow channel is designed to enable the liquid nitrogen to flow through the close vicinity for economical consumption of the liquid nitrogen without affecting the cutting mechanism during turning operation. The schematic view of the cryogenic set-up is exhibited in Fig.1.

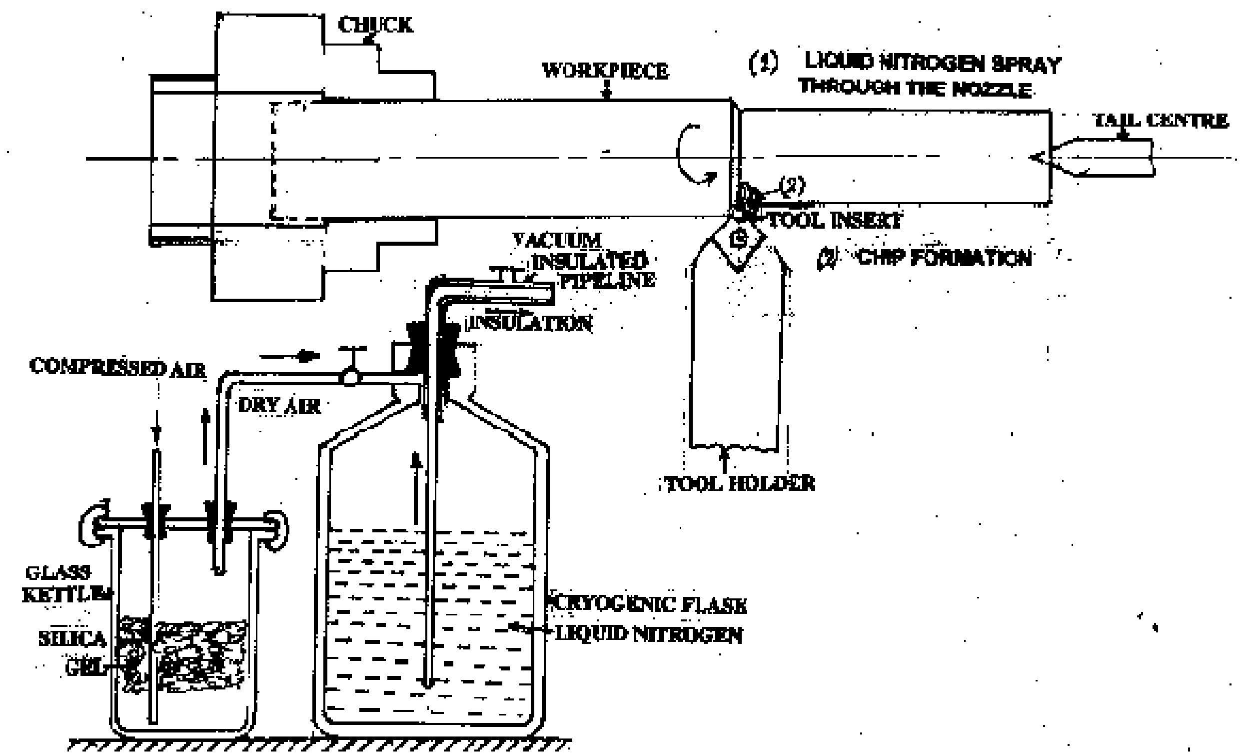

Fig. 1 Schematic View of the Experimental Set-up with Cryogenic Cooling Arrangement

The striking feature of this cryogenic cooling arrangement is that consumption of liquid nitrogen is comparatively lower and effective chip breaking can be possible which intern reduce the sliding, ploughing and rubbing of the chips with the tool insert as well as with the finished surface. Hence, there is no chance of alteration of the microstructure or surface integrity of the workpiece and tool material due to alteration of high tempering and very low cooling effect due to flood cooling. By this development, the temperature of the cutting tool can be reduced to a moderate temperature level which in tern save the production cost due to better tool life, less idle time and better surface quality.

PLANNING FOR EXPERIMENTAL STUDIES

The experimental conditions selected for different test runs designed for both the dry and cryogenic environment are listed in Table 1. Tungsten Carbide Inserts of specification CC MT 090304 TK 15/TN 200 are used as the cutting tool. The job material for the turning experiment was High Strength Steel, i.e. H_{11}, technically known as hot die steel. As in the initial i.e raw material state it has low hardness but provision for increasing its hardness. To achieve high hardness value, the job material is heat treated. The maximum attainable hardness by the above mentioned process of the job specimens used for final metal cutting experiments is about RC 56 to RC 57.

Before starting the turning operation under cryogenic condition, liquid nitrogen spray/jet was applied over the rotating workpiece by moving the nozzle form right to left and left to right uniformly to bring down the ductility of the workpiece and for easiness of chip breaking to form discontinuous chips.

TABLE-1 : Experimental Conditions

ITEMS	DESCRIPTION
Machine	PL-4 Lathe Manufactured by LAXVARD Industries, Bangalore.
Spindle Speeds	234,340,378,488,532,718,765 and 1045 r.p.m.
Cutting Speeds	50, 55, 60 and 65 m/min.
Depth of Cuts	0.75, 1.0 and 1.25 mm.
Length of Cut	Constant at 100 mm.
Feed Rate	Constant at 0.1 mm/rev.
Equipments used	Brinell Microscope and Scanning Electron Microscope (SEM)
Environment	Dry and Liquid Nitrogen Flow

For the investigation on tool wear, some sets of experiments are performed under both dry and cryogenic conditions. After each set of experiments tool wear is measured through a Brinell Microscope for both the dry and cryogenic environment. Scanning Electron Microscope (SEM) is used for observing the nature of tool wears and condition of cutting edge of tool inserts after turning operation for the same set of experiment i.e. 60 m/min cutting speed, 100 mm length of cut, 1.25 mm depth of cut and 0.1 mm/rev feed rate under both dry and cryogenic environment.

THEORITICAL APPROACH FOR THE TEPERATURE DISTRIBUTION

For simplifying the problem, in the present paper a process of steady state two-dimensional orthogonal machining in the presence of cooling is considered. The governing energy equation, assuming temperature independent thermal properties and ignoring radiation is written as;

where ρ is the mass density, c_p is the specific heat

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)-k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=Q$$

at constant pressure, k is the thermal conductivity, T is the temperature, x and y are the Cartesian coordinates, u and v are the velocity components in the x and y directions respectively, Q is the total heat generation rate per unit volume. The total rate of heat generation (Q) can be expressed as the sum of the energy consumed in the primary heat zone (q_1) and secondary deformation zone (q_2). According to shaw, q_1 and q_2 can be expressed by the equation: $Q = q_1 + q_2$, where, F_S is the component of force directed along the shear plane, V_S is the velocity of the chip relative to the work piece, which is directed along shear plane, j is the mechanical equivalent of heat, b the width of cut, t is the depth of cut, a the length of contact between the chip and tool in the direction of motion, which is equal to the length OE, F_C , the friction force along the tool face and V_C , the velocity of the chip relative to tool.

Shear angle ϕ can be determined by Ernest and Merchant equation by the expression $\phi = 45 - \beta/2 + \gamma/2$, $\beta = \mathrm{Tan}^{1}(F_C/N_C)$, $N_C = F_X \cos\gamma - F_Y \sin\gamma$, where β is the friction angle and N_C is the force perpendicular to the rake face. In the figure 1, ODCB forms the outline of the CBN insert, BCML forms the outline of the tool holder which supports the insert, EGHIJKO forms the outline of the work piece. A is a point on the rake 2 mm away from the tip where a thermocouple for temperature measurement is located. F_N is the component of force directed normal to the shear plane, F_X and F_Y are the cutting and thrust forces measured by a Kistler Dynamometer, ϕ, the shear angle and V, cutting speed.

The above-mentioned energy equation can be solved With boundary conditions: (i) $T = T_A$ on S_T, where ρ is the mass density, C_p is the specific heat, k is the thermal conductivity, h and h_a are the heat transfer coefficients assigned to the boundaries which are

$$-k\frac{\partial T}{\partial n}=0$$

$$-k\frac{\partial T}{\partial n}=h(T-T_N)$$

$$-k\frac{\partial T}{\partial n}=h_a(T-T_A)$$

exposed to liquid nitrogen and to ambient air, respectively, x and y are the Cartesian coordinates, u and v are the velocity components in the x and y directions respectively, and n stands for the normal direction to the S_O –type boundaries. The work piece temperature far away from the cutting edge, T_A, can be equated to the ambient temperature (25^0C). T_N is the liquid nitrogen temperature for cryogenic cutting. The approximate assumption of the thermally insulated condition on S_O class boundaries is justified by the fact that the temperature gradient on these boundaries becomes negligible, compared to these near the tool-chip interface and the shear plane, if they are far enough away from the cutting edge and the two heat sources.

For a dry cutting process, the boundary can be classified as:

(a) HG, GF applies for the S_T

(b) (b) AB, JK, KL, EF applies for the S_O

(c) HI, IA, BC, CJ, LD, DE, applies for the S_A

and for the cryogenic cutting process, the following applies for the boundary classification:

(a)HG, GF applies for the S_T

(b) AB, JK, KL, EF applies for the S_O

(c) HI, LD, DE applies for the S_A

IA, BC, CJ applies for the S_H

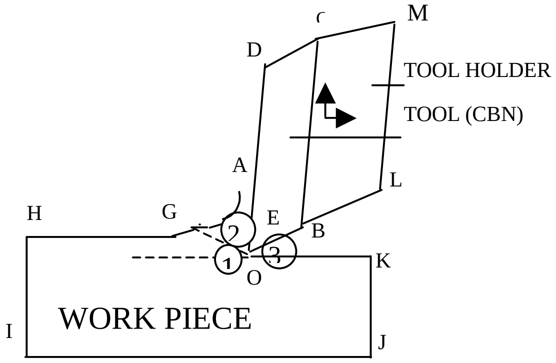

Fig. 2 Cutting process

For simplicity, the velocity field throughout the work piece domain IDEFGHI is considered to be in the cutting direction with the same magnitude as the surface cutting speed $\mathbf{V_C}$**, i.e. u = 0, v =** $\mathbf{V_C}$. In the chip domain IABCDI, the velocity is assumed to be in a direction that varies continuously and tangentially to the middle line of the chip arc thickness and has a constant magnitude V_{Chip}, equal to the chip flow speed and can be determined from the cutting ratio r as follows: $\mathbf{V_{Chip} = rHV_C = Sin\beta/Cos(\beta\text{-}\gamma)HV_C}$, where, β and γ are the shear and the effective tool rake angle, respectively. Also, the following equations apply for the chip domain IABCDI: $\mathbf{u = V_{Chip}HCos\delta}$**,** $\mathbf{v = V_{Chip}HSin\delta}$, where δ is the angle tangential to the chip central line.

Mathematically, the heat transfer problem can be solved from the calculus of variations by minimizing, with respect to T, the functional I(T):

$$I(T)=\iint_A \rho c_p\{(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})-k(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})\}dA$$

Where, A is the problem region of machining. The heat transfer coefficient h on the boundaries exposed to the liquid nitrogen jet was approximated by the experimental estimate of the heat transfer for a parallel liquid nitrogen flow on a flat surface of finite length. For a liquid nitrogen flow rate of 2.05 X 10^{-5} m^3/s (0.325 gallon/min), the average heat transfer was estimated to be between 4.827 X10^4 and 7.495 X10^4 W/m^2K, depending on the surface temperature which was altered from –180 to 650^0C in the experiment.

The finite element method (FEM) involves a numerical discretization of I(T). It suffers here to note that FEM can be reduced to the equation : [H] {T} = {P}. where, [H] is the thermal stiffness matrix and {T} is the column vector composed from nodal temperature. {P} represents the load contributed by the above mentioned heat sources and can be simply lumping the deformation heat Q_S and the friction heat Q_f to the nodes located in the shear plane ID and the tool-chip interface CD respectively.

TEST RESULTS AND DISCUSSION

Analysis of Tool Wear

It has been observed from Fig. 2(a) to Fig. 2(c) that the tool wear increases with the increase of cutting speed and depth of cut and for a constant length of cut and constant feed rate. With the increase of cutting speed the chips become more ductile than the parent material due to very high amount of heat generation and tends to formed into overly broken to well broken and well broken to poorly broken type which in tern increases rubbing, sliding and ploughing of the chips with the tool and finished surface. So the tool wear increase rapidly under dry condition but under cryogenic condition it still increases slowly as the liquid nitrogen helps to reduce the chip temperature nearly its embrittlement temperature and increase the chip breakability which in tern chip are formed in to discontinuous and small fragments.

Fig. 2 clearly exhibits that for 100 mm length of cut and 0.75 mm depth of cut machining condition, as the

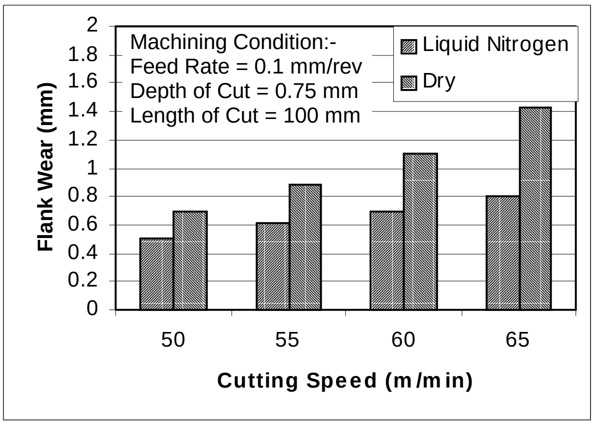

Fig. 3(a) Flank wear vs. cutting speed

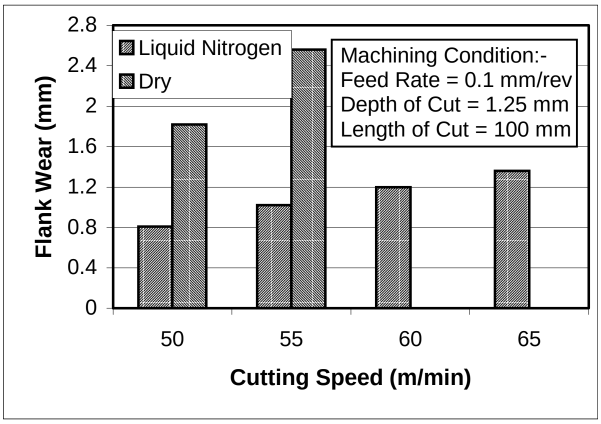

Fig. 3(c) Flank wear vs. cutting speed

cutting speed increases, rubbing of the cutting edge of tool inserts with the job surface and also with chip increases due to poorly broken and longer chip formation. Hence, increases the temperature of cutting zone results increase of tool wear under dry environment. But in cryogenic cooling, temperature of the tool insert may not increase sufficiently due to continuous liquid nitrogen supply and rubbing action decreases as the chips are formed into small fragment,. Also the mechanism of material removal is by ideal shearing but less by ploughing, sliding and rubbing. That is why the tool wear is lower compared to the tool wear under dry machining condition.

If the depth of cut be selected as 1.0 mm then rapidly increasing tool wear-out condition is observed above 55 m/min cutting speed for both machining environments. The differences between the tool wears obtained under dry and cryogenic environment at the particular machining condition increase. Though the tool wear lines under dry condition are increasing sharply but under cryogenic condition it still increasing gradually, as shown in Fig.2(b). The reason is that under dry condition more amount of heat is generated and the chips are formed into well broken, whereas under cryogenic cooling chips are formed into overly broken and small fragments.

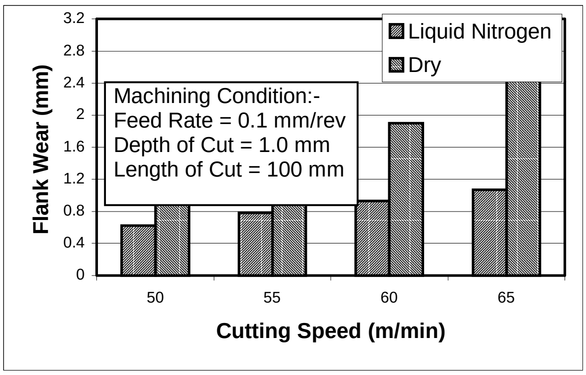

Fig. 3(b) Flank wear vs. cutting speed

At 1.25 mm depth of cut and 100 mm length of cut, cutting edge of the tool wears out rapidly and is completely damaged above 55 m/min cutting speed and machining is impossible under the dry condition. At 1.25 mm depth of cut, rubbing action is very high in addition to sliding and ploughing due to continuous and longer chip formation. Also, at this depth of cut vibration of the machine tool appears to be more and increases rapidly with the increase of cutting speed. As the rubbing action is higher due to larger cutting depth in this machining condition, more amount of heat is generated in addition to high cutting force which in turn leads to complete damage of the cutting edge of the tool insert. Above this cutting speed, i.e. 55 m/min, the tool wear with mechanical breakage and plastic deformation becomes so large that it can not be used for further turning operation of the workpiece material as it did in the earlier parametric conditions as shown in previous graphs. But under the cryogenic condition, tool wear till increases gradually with a lower rate due to overly broken or well broken type chip formation as shown in Fig. 2(c).

CONCLUSIONS

From the above mentioned test results, it is observed that with the increase of cutting speed, depth of cut and length of cut, tool wear increases. It is also clear from the test results that tool wear rate of the tungsten carbide inserts for turning very hard material, i.e. high strength steel (H_{11}), is lower under the cryogenic environment compared to the dry environment for the same machining parametric condition. In all the experimental test results it is also observed that tool wear phenomenon is reduced up to 30-35% under the cryogenic environment compared to the dry environment for the same machining parameters as shown in the Fig. 2(a), 2(b) and 2(c). Study of SEM micrographs of cutting tool inserts clearly indicates the influence of cryogenic cooling on the tool wear. Micrographs exhibit various defects and wears occurred along the cutting edges of the tool inserts at dry as well as cryogenic environment. From the study of the micrographs, it can also be concluded that cryogenic cooling of tool inserts reduces the phenomena to a greater extent and that the insert can be reused for producing the jobs economically.

The experimental set-up should be such that the coolant circulation through the flow channel to the cutting zone must be continuous and must not be blocked by frozen ice. Also the liquid nitrogen spray/jet should be freed only on the selected area of the chip faces and not on the whole area of cutting zone to minimize the liquid nitrogen consumption and proper utilization. Some further development is necessary in these direction for improving the efficiency of this cryogenic cooling system.

Selecting the nozzle aperture and zone of application can reduce the consumption of liquid nitrogen.

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