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Enhancement of Tool Material Machining Characteristics with Cryogenic Treatment: A Review

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Abstract

For cost effective machining it is necessary to identify and quantify changes in tool material machining characteristics. Cryoprocessing, a supplementary process to conventional heat treatment, involves deep-freezing of materials at cryogenic temperatures to enhance the mechanical and physical properties. The execution of cryoprocessing on cutting tool materials increases wear resistance, hardness, and dimensional stability and reduces tool consumption and down time for the machine tool set up, thus leading to cost reductions. The present research paper reviews the machining characteristics of tool material with cryogenic treatment for industrial applications.

Keywords
Machining characteristics, cutting tool material, cryogenic treatment, down time, cost reduction

1. Introduction
Tools wears constantly, when are being used in manufacturing, cutting and forming processes [1]. With the advancement in metal machining and cutting operations it is necessary to identify and quantify changes in the microstructure of metal alloys used in metal cutting and shaping processes [2]. There are number of treatment processes used for different metals which cause them to behave differently under different conditions [3]. However, the mechanism of microstructure changes in alloys under various treatments, are not yet fully understood [1]. Change in microstructure effects on tool life under certain treatments [4]. Empirical studies have demonstrated that the life of cutting tools like high speed steel (HSS) and tungsten carbide (WC) can be increased by cryogenic treatment [5]. Reducing tool wear is important in various manufacturing processes in order to increase tool life which in turns reduces cost of production [6]. The efficiency of the tool depends upon the time for which it is used for cutting or in other words, longer is the cutting time, better is its performance. However, while the wear of the cutting edge gradually increases, the precision and the quality of the surface finish of the work piece decreases [7]. Sooner or later, the tool has to be changed or turned so that a fresh edge can be used. The life time of a cutting tool is consequently an important economic factor, creating huge competition among cutting tool producers [2]. The tools have to withstand high temperature and stress during cutting, and have to absorb cutting forces produced during machining [1]. Also tool material must be corrosion resistant and chemically inert towards the work piece material [7]. Moreover, the metal working industry demands not only a long tool life, but also trying to increase the limits of the tools still further, as higher and higher cutting speeds are required for high speed machining which causes decrease in cycle time and increase in production [8]. The two most commonly used tool materials are coated/uncoated carbides and HSS [9]. With these new possibilities and because of the strong competition, the cutting tool industry is highly interested in fundamental research about the wear of these materials in order to gain a better understanding of the mechanisms leading to the destruction of the cutting edge and to find ways to prolong the life-time of the tools [2].

1.1 Cryogenic treatment
Cryogenic treatment may be oversimplified into a process of chilling a part down to relatively near absolute zero and maintaining that condition until the material has cold-soaked [10]. The temperature is then allowed to rise until ambient equilibrium is reached [11-13]. The part may then be subjected to a normal tempering reheat, although this step is not always included in the process. The complexity of the process involves determining and achieving the proper duration for the cooling, soaking and warming cycles [14-16]. It is here that developments in computer

modeling and controls have placed cryogenic tempering on the cutting edge of metal treatment. Meng et al. conducted an experiment on alloy tool steel with composition 1.44C, 0.3Si, 0.4Mn, 12.2Cr, 0.84Mo, 0.43V, 0.022P and 0.008S and compare the results after cold treatment (223K) and after cryogenic treatment (93K). The cryogenic treatment results show 110 to 600% improvement. The wear rate shows a minimum at the sliding speed of 1.14 and 1.63 m/s for specimens without and with cryogenic treatment, respectively [13]. Singh, highlighted that the tool life of a single point cutting tool has been increased by 333% & amount of material removed in single setting of tool increased from 321.78 gm to 1392.30 gm after applying cryogenic treatment to cutting tool [7].

The process is based on a predetermined thermal cycle that involves cooling of the tools/parts in a completely controlled cryogenic chamber [15]. The material is slowly cooled to -300ºF and 'soaked' at that deep cryogenic temperature for 20-40 hours. The material is then allowed to return very slowly to ambient temperature. The complete cryogenic cycle can take up to 70-75 hours to complete [16-18]. This procedure of precisely controlled temperature profiles avoids any possibility of thermal shock and thermal stress that is experienced when a tool or part is subjected to abrupt or extreme temperature changes. In this process liquid nitrogen is used as a refrigerant [19-20].

Cryogenic processing is not a substitute for heat treatment, but rather an extension of the heating / quenching / tempering cycle. In most instances the cryogenic cycle is followed by a heat tempering procedure [21].Kamody described an expedited process for the cryogenic treatment of metal-containing material, preferably in a bath of liquid nitrogen, to improve shock ability, wear ability, stability and hardness of at least the surface of the article. Kamody does not appreciate the advantages of tempering and, if necessary, re-tempering the treated article at elevated temperatures [20]. As all alloys do not have the same chemical constituents, the tempering procedure varies according to the materials chemical composition, thermal history and/or a tools particular service application [22].
Figure 1 shows the schematic of cryogenic equipment [23]. It comprises of an insulated box, one motor with a circulating fan, one thermocouple to measure the cryogenic temperature inside the box connected to a temperature controller and programmer, a liquid nitrogen tank and a solenoid valve for the gas inlet.

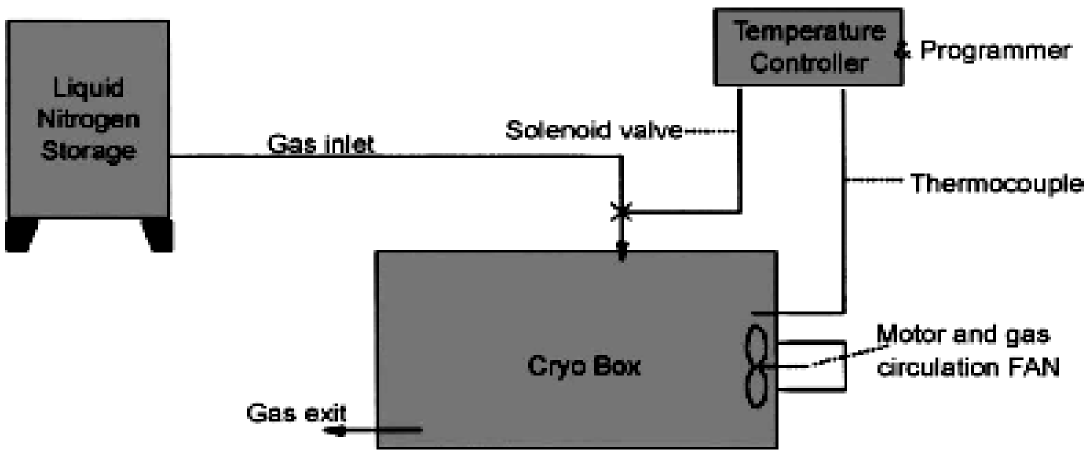

Figure 1: Schematic of cryogenic equipment [23]

Figure 2 shows typical cryogenic cycle used for industrial application [2]. Cooling rate is one of the most critical parameter, which must not exceed 20-30C°/h in order to prevent the rupture of the components because of the cooling stresses. The ramp down time is 9 hours. A temperature of –184 C° is achieved in 9 hours. After ramping down to (-184 C°), material is soaked at this minimum temperature for 18 hours. It is again brought up to the room temperature in 9 hours known as the ramp up temperature. The total duration of the cryogenic treatment is about 36 hours. After the material is cryogenic treated, it is tempered to 150 C°. The temperature of 150 C° is achieved in 1.5 hours and it is kept at this temperature for 4 hours. The material is brought back to room temperature in the next 1.5 hours. The total duration of tempering cycle is 7 hours. Tempering is done in order to remove the stresses developed during cryogenic cooling. The total duration of the Cryogenic-tempering cycle is 43 hours. Tools are cryogenically treated in accordance with A S M Standard.

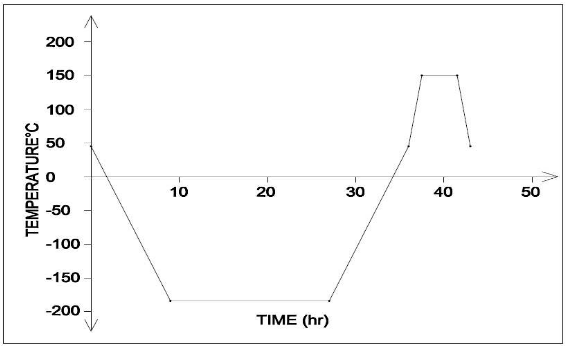

Figure 2: Time Vs Temperature for cryogenic cycle [2]

1.2 Microstructure Changes

Two main changes in the microstructure of the steel occur as a result of cryogenic treatment [2, 7]. These changes are the principal reasons for the dramatic improvement in wear resistance.

- **Retained Austenite**

Retained austenite is a softer grain structure always present after heat treatment. By applying cryogenic treatment, retained austenite is transformed into the harder, more durable grain structure - martensite. The range of retained austenite in a material after heat treating may be as high as 50 % or as low as 3 %. Figure 3 shows the atomic structure of austenite crystal and martensite crystal.

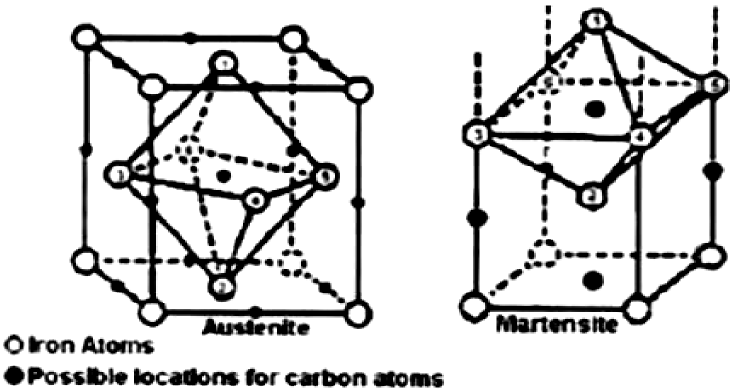

Figure 3: Atomic structure of Austenite crystal (left) and Martensite crystal (right) [2]

The amount depends on the heat treating operator and the accuracy of the heat treating equipment. Cryogenic treatment simply continues the conversion initiated by heat treatment, whereby almost 100 % of the retained austenite is converted to martensite. As greater amounts of retained austenite are transformed, and wear resistant martensite is increased, the material obtains a more uniform hardness.

- **Fine Carbide Precipitates**

Fine ‘neta’ carbide particles (precipitates) are formed during the long cryogenic soak (chromium carbides, tungsten carbide, etc., depending upon the alloying elements in the steel). These are in addition to the larger carbide particles present before cryogenic treatment. These fine particles or "fillers", along with the larger particles, form a denser, more coherent and much tougher matrix in the material. Many researchers and scientists have done lot of work on cryogenic treatment [10-22]. Some literature data indicates that wear resistance of several metals and alloys increase significantly after being subjected to subzero (below 0ºC) temperatures. The results are beneficial for decreasing machining cost and depending on the application. Increase in tool life depends upon the material composition, size and weight of material, and cryogenic cycle used in the treatment. Reports of 92–817% increases in tool lives after they have being treated at −196ºC are found.

Molinari et al. applied deep cryogenic treatment to two different cold work tool steels, X155CrMoV121 and X110CrMoV82. The effect is more pronounced when DCT cycle is carried out immediately after quenching. DCT mainly enhance destabilization of martensite, by activating carbon clustering and transition carbide precipitation [12]. Zhu et al. [24] investigated the effect on mechanical properties and microstructure of Fe-Cr-Mo-Ni- C- Co alloy after quenching in liquid nitrogen for 24 hr. The result shows that hardness increased by 1-2 HRC and compressive strength decreased slightly after cryogenic treatment. The increase in hardness is attributed to the transformation from austenite to martensite and precipitate of the very tiny carbide η-Fe2C.The decrease in compressive strength is caused by residual stress.

2. Case Study on Machining Cost Reduction of Crank Shaft

The study was conducted for crank shaft machining, after deep cryogenic treatment of tools. The study highlights 20%- 22% increase in tool life. Further cost per component is decreased up to 14.75% [2]. There are five machining operation of crank shaft (Figure 4).

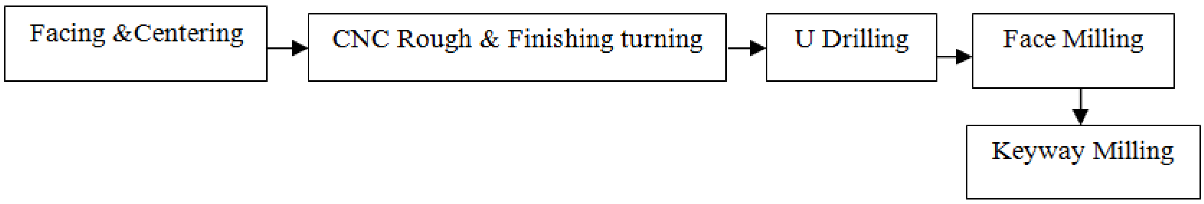

Figure 4: Machining process flow of crank shaft [2]

- **Effect of cryogenic treatment on wear rate of carbide inserts used for CNC machining**

Table 1 shows tool life of various tools used in crankshaft machining. It has been observed that with the increase in cutting speed from 250 m/min to 290 m/min, flank wear increases. Untreated inserts and cryogenic treated inserts shows same trend. Initially flank wear of both types of inserts is same but with increase in production or near the end of tool life, cryogenic treated inserts has less flank wear as compare to untreated inserts.

Table 1: Tool life of various tools used in crank shaft machining [2]

Operation	**Tool**	**Tool Life**		**% Increase in tool Life**
		Before Treatment	**After Cryogenic Treatment**	
Facing & Centering	HSS centre Drill	175 pcs/edge	200 pcs/edge	14.2%
	Carbide Insert	375 pcs/edge	425 pcs/edge	13%
CNC Turning	Carbide Insert	65 pcs/edge	73 pcs/edge	12.3%
	Carbide Insert	90pcs/edge	110 pcs/edge	22.2%
	Carbide Insert	80 pcs/edge	84 pcs/edge	5%
U Drilling	Carbide Insert	175 pcs/edge	205 pcs/edge	17.1%
Face Milling	Carbide Insert	220 pcs/edge	255 pcs/edge	15.9%
Key way Milling	HSS cutter	1600 pcs	1920 pcs	20%

Effect of cryogenic treatment on cost per component of crank shaft

Average Production of crank shaft per month = 2, 50,000 pcs

Cost saving per component = Machining cost before cryo treatment - Machining cost after cryo treatment

= (2.38 - 2.03) = 0.35 Rs (INR)

Total saving per month = 87,500 Rs (INR)

Table 2 shows effect of cryogenic treatment on machining cost per component

Table 2: Machining cost per component

Operation	Tool	Cost per Component (Rs)	
		Before Treatment	After cryogenic treatment
Facing & Centring	HSS centre Drill	0.344	0.2561
	Carbide Insert	0.116	0.098
CNC Turning	Carbide Insert	0.417	0.259
	Carbide Insert	0.417	0.172
	Carbide Insert	0.201	0.183
U Drilling	Carbide Insert	0.35	0.29
Face Milling	Carbide Insert	0.286	0.23
Key way Milling	HSS cutter	0.667	0.544

Total = Rs 2.38 (INR) Rs 2.03(INR)

Conclusions

Following are the conclusions for the study:

- Cryogenic treatment improves mechanical properties like wear resistance, toughness and resistance to fatigue cracking. This is due to the, transformation of retained austenite into stable martensite. The phase transformation leads to the increase in density of dislocations and vacancies which in turns enhance the diffusion coefficient of carbon. This microstructure evolution induces the precipitation of very tiny carbides during the cryogenic treatment.
- For WC tools, cryogenic treatment effects on cobalt binder which in turns enhance tool life [24]. The precipitations of η phase at sub zero temperature might have improved the flank wear. The different cryogenic cycle might have affected the amounts and distributions of these carbides and appeared to have altered some of the properties of carbide tools.
- Cryoprocessing, if properly employed, can provide significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cryoprocessing.
- Overall, cryoprocessing has significant favorable influence on the performance of cutting tool steels and carbides. Hence, cryoprocessing is a good alternative for having productivity enhancement.
- The improvement in wear resistance and hardness by cryoprocessing is attributed to the combined effect of conversion of retained austenite to martensite and precipitation of η-carbides in case of tool steels. The phenomenon responsible for improved wear resistance in carbide cutting tools is the combined effect of increased number of η phase particles and increase in bounding strength of binders used.
- Cryoprocessing is an inexpensive one-time permanent treatment affecting the entire section of the cutting tool unlike coatings; therefore, similar lives can be expected after each regrinding of tools.
- Overall, cryoprocessing has significant favorable influence on the performance of cutting tool steels and carbides. Hence, cryoprocessing is a good alternative for having productivity enhancement.

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