International Journal of Mechanical and Production Engineering, ISSN: 2320-2092, Volume-1, Issue-1, July-2013

EFFECTS OF CRYOGENIC ON TOOL STEELS-A REVIEW

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Abstract— This paper studies the effect of cryogenic treatment on tool steels, many researchers shows their findings and optimized parameters affecting the properties of various tools steels under different machining process. Cryoprocessing is a supplementary process to conventional heat treatment, since it converts the retained austenite into martensite which is remain after heat treatment and due to martensite formation there is an increase in wear resistance, hardness, dimensional stability, and reduces tool consumption and hence extending intervals between replacements of tools which reduces the down time for the machine tool set up thus leading to cost reductions, which is an important consideration in industry. The effectiveness of these properties is improving by use of modern technology such as microprocessor, microcontroller to control temperature profile which avoids thermal shocks created. Some researcher developed their own system to control the drawback of cryogenic treatment such as developments of cutting forces are reduce by use of secondary liquid nitrogen supply. Various methods are incorporated to maintain low temperature such as use of liquid nitrogen, dry ice, adding nano particles to conventional cutting fluid.

Index Terms— Cryogenic treatment, Liquid nitrogen, Tool steel, Wear resistance etc.

I. INTRODUCTION

Tools wears constantly, when are being used in manufacturing, cutting and forming processes, reducing tool wear is important in various manufacturing processes in order to increase tool life for reducing the cost of production. The efficiency of the tool depends upon the time for which it is used for removing of material, as the wear of the cutting edge gradually increases, the precision and the quality of the surface finish of the work piece decreases, the tools have to withstand high temperature and stress during cutting, and have to absorb cutting forces produced during machining. Also tool material must be corrosion resistant and chemically inert towards the work piece material [1].The primary objective of the heat treatment of die/tool steels is to impart high wear and abrasive resistance, but one of the major problems in the conventional heat treatment through hardening and tempering of these steels is the content of retained austenite, which is soft, unstable at low temperature and transforms into brittle martensite during service. Transformation of austenite to martensite is associated with approximately 4.3 % volume expansion, which causes distortion of the components. Thus sub-zero treatment or cryogenic is used for minimizing the amount of retained austenite content in tool steels. Cryogenic processing had its US origins in the 1940s. Cryogenic processing will make the metal harder & therefore more brittle, Cryogenic processing has no effect on low carbon steel, cast iron and non ferrous metal. Cryogenic processing makes changes to the structure of the materials being treated and dependent on the composition of the material, it performs three things; retained austenite turned to martensite, carbide structures are refined and stress is relieved. Cryogenic processing will not in itself harden metal like quenching and tempering, it is an additional treatment to heat-treating. The benefits of this process includes; reduction of abrasive and adhesive wear, improved machining properties resulting from the permanent change of the structure of the metal, reduction of the frequency and cost of tool remanufacturing and reduction of catastrophic tool failure due to stress fracture [2],[3]. A specific percentage of retained austenite may be desired for applications such as bearings or gears where the metal may require some toughness to absorb impact or torsion loading [4].

A. Sub Zero Treatment

Sub-zero treatment of steels is a process that is gaining acceptance in the United States and is increasingly being applied in Europe, Latin America and Asia. The sub-zero treatment processes can be grouped into three broad categories on the basis of temperature and soaking time as they impact steel in the following ways

- *Shrink fitting*

Reduces the diameter of a steel shaft so workers can readily assemble it with other components.

- *Cold treatment*

Completes the metallurgical phase transformation of austenite into martensite during the hardening of steels via quench and temper heat treatment.

- *Cryotreatment*

At liquid nitrogen temperatures creates conditions for the subsequent nucleation of very fine carbides in high alloy steels [4].

Cryogenics is a relatively new process used to eliminate retained austenite; in which the temperature has to be lowered. In cryogenic treatment the material is to be deep freeze temperatures of as low as 90 K. A cryogenic processor is used to reach ultra-low temperatures of about 125 K. The cooling is performed at slow rate to prevent thermal shock to the components being treated. The first commercial unit was developed by in the late 1960s. The development of programmable microprocessor controls allows the machines to follow temperature profiles that greatly increased the effectiveness of the process. Before programmable controls were added to control cryogenic processors, the "treatment" process of an object was done manually by immersing the object in liquid nitrogen. This normally caused thermal shock to occur within an object, resulting in cracks to the structure. Modern cryogenic processors measure changes in temperature and adjust the input of liquid nitrogen accordingly to ensure that only small fractional changes in temperature occur over a long period of time .Cryogenic processors come in a variety of sizes and configurations. The processors are typically designed to accommodate batch or continuous loads and come in two styles, front loading and top loading. The appropriate design depends upon the production volume and part configuration of a plant [6].

B. The cryogenic processor

Consists of a treatment chamber, which is connected to a liquid nitrogen cylinder through a vacuum insulated tube. The thermocouple inside the chamber senses the temperature and accordingly the temperature controller operates the solenoid valve to regulate the liquid nitrogen flow. The programmable temperature controller of the cryogenic processor can be used to set the cryogenic treatment parameters, which in turn controls the process parameters. Fig. 1 shows the schematic diagram of the cryogenic processor [8].

Obviously, the conversion of retained austenite is a factor for steel. But most retained austenite is converted by cold treating. Cold treating of metals has been known for many years, and takes place at around 180 K. Research shows that the wear resistance of cold treated steels is only a fraction of that of cryogenically treated metals .The martensite reaction occurs as the FCC (face centered cubic) austenite transforms to a BCT (body centered tetragonal) martensite. Carbon atoms are trapped in interstitial sites during the rapid transformation. Two main changes in the microstructure of the steel occur as a result of cryogenic treatment, these changes are the principal reasons for the dramatic improvement in wear resistance [1], [3], [5].

- *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 3 to 50 %. Fig. 2 shows the atomic structure of austenite crystal and martensite crystal. The amount depends on the heat treating operator and the accuracy of the heat treating equipment [1].

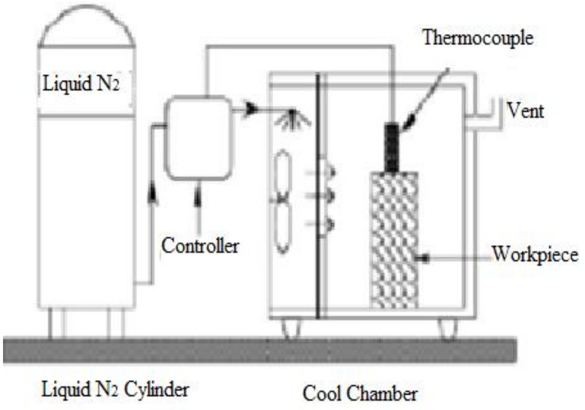

Figure 1Schematic diagram of cryogenic processor [8]

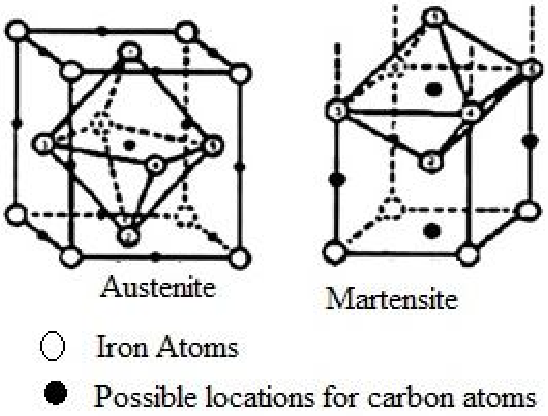

Figure 2Atomic structure of Austenite crystal (left) and Martensite crystal (right) [6]

- *Fine Carbide Precipitates*

  Fine ‘neta’ (η) 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 [1].

II. METHODS FOR PRODUCING LOW TEMPERATURE

There are a variety of methods to bring parts down to the desired processing temperature. However, all methods work on the same thermodynamic principles of heat transfer. All low temperature equipment falls into two broad categories direct or indirect cooling.

- *Direct Cooling*

Processors can use liquid nitrogen effectively to achieve the temperatures necessary for cryotreatment and to get quick cool down rates for cold treatment. One of the most common techniques is to use a spray header system with atomizing nozzles that convert the liquid nitrogen (LIN) to very cold gas, cooling the parts as the liquid nitrogen flashes to a vapor and warms up. The LIN is directly converted to cold gas to cool the parts. Only the cold gas and not the fine droplets of LIN should come in contact with the part surface to avoid “spot martensite” formation. Technicians can control the temperature in such a box by implementing a proper nitrogen flow. Direct cooling is the most efficient means to achieve low cryogenic temperatures for controlled processing [4].

- *Indirect Cooling*

Mechanical freezers are an example of indirect cooling. Nitrogen and mechanical means can both be used to cool an alcohol tank where parts could be submerged for cold treatment. Carbon dioxide in the form of dry ice has also been used to create the cooling power for cold treatment. Since the temperatures of these techniques can go about 153 K some freezers according to size & opening s are as shown in Fig. 3 [4].

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Figure 3Devices for freezing [4]

III. EFFECTS OF CRYOGENIC ON PROPERTIES OF TOOL MATERIALS

D. Das *et al.* [2] investigates during his experiment that wear resistance of the AISI D2 steel gets considerably enhanced by cryotreatment, compared to that of the conventionally treated one, irrespective of the time of holding at 77 K, is attributed to the near absence of retained austenite and more homogeneous distribution of a larger number of finer secondary carbides in the former specimens. Also hardness of the investigated steel samples is found to increase marginally by cryotreatment in contrast to significant increase in their wear resistance.

N.R. Dhar *et al.* [7] shows experimental investigation on the role of cryogenic cooling by liquid nitrogen jet on tool wear and product quality in plain turning of AISI 1040 at various industrial speeds feed combinations by two types of carbide inserts of different geometry, founds 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, high reduction in flank wear, which would enable remarkable improvement in tool life. 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. Such reduction in tool wear might have been possible for retardation of abrasion and notching, which are very detrimental and may cause premature and catastrophic failure of the cutting tools, are remarkably reduced by cryogenic cooling. 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.

Simranpreet Singh Gill [8] during his experiment founds that Soaking temperature, soaking period, cooling rate, tempering temperature contributes for the improvement of flank wear resistance,& Conclude that the cryogenically treated AISI M2 HSS tool samples as per the arrived optimum conditions improve in wear resistance by about 47%. The Taguchi design results confirmed that soaking temperature appreciably reduces the flank wear with contribution of 72.04%, followed by soaking period with contribution of 23.78%. The third major factor was cooling rate with contribution of 9.54%. The least significant factor acknowledged was tempering temperature with contribution of 2.74% whereas tempering period was found out to be trivial.

Panchakshari H.V *et al.*[9] Uses Taguchi’s and S/N (signal to noise) ratio methods used to determine the optimal process parameters which minimize the number of experimentations to be conducted to determine the wear properties of cryogenically treated Al/Al_2O_3 composites. After determining the optimum process parameters, one confirmation experiment was conducted. The optimum level of cryogenic process parameters to obtain good wear resistance of Al /Al_2O_3 are 20 % wt. of Al_2O_3 particles, cryogenic temperature of 123 K and treatment duration of 50 hours. Wt. % of Al_2O_3 is contributed on wear resistance (73%), cryogenic temperature (20.3%) and cryogenic treatment duration (5.783 %). The pooled error associated with the ANOVA is 0.5 % for the factors.

Kamaljit Singh *et al.* [11] from the experiment he concluded that cost per component decreased by 20.8% after cryogenic treatment of the tools used for crank shaft machining. Also flank wear resistance of HSS inserts increased up to 20%. Saving per month after cryogenic treatment of tools is approximately Rs 52,500/-.

Shane Y. Hong *et al.* [12] developed an economical cryogenic machining approach, according to this approach a minimum amount of LN2 (secondary liquid nitrogen) injected through a micro nozzle formed between the chip breaker and the tool rake and assisted by the secondary nozzle for flank cooling. In this manner, LN2 is not wasted by cooling unnecessary areas and reduces the negative impact of increasing the cutting force and the abrasion of pre cooling the workpiece material. Which is beneficial since due to this less cutting forces are generated as in case of cryogenic treatment. The arrangement is as shown in Fig.4.

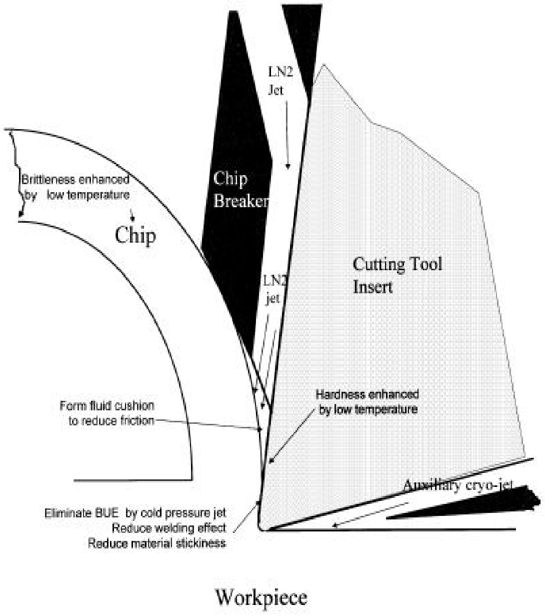

Figure 4A Schematic of the economical cryogenic machining approach [12]

Y. Yildiz *et al.* [14] in his study uses Be-Cu alloy as workpiece subjected to around 172 K for cold treatment and to around 88 K for cryogenic treatment and the effects of cold and cryogenic treatments on their machinability in EDM(electric discharge machining) have been investigated. Experimental results showed about 20 & 30 % increase in material removal rate by cold and cryogenic treatment processes. Variations in electrode wear rate, surface roughness and average white layer thickness were found to be marginal.

S. Khandekar *et al.* [15] does in his experiment, a comparative study of the performance during dry machining and machining with conventional and nano cutting fluids. He found that adding 1% Al_2O_3 nanoparticle (by volume) to the conventional cutting fluid greatly enhances its wettability characteristics compared to pure water and conventional cutting fluid. The great reduction of crater and flank wear is attributed to enhanced thermal properties, improvement in wettability, and lubricating characteristics of the nano cutting fluid, Causes a reduction of 50% and 30% in cutting force while machining with nano cutting fluids compared to dry machining and machining with conventional cutting fluid, respectively. Also there is 54.5% and 28.5% reduction in the Ra value of the machined surface when nano cutting fluid is used compared to dry machining and machining with conventional cutting fluid, respectively.

Mr. Sandip B.Chaudhari *et al.* [16] founds 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. Cryogenic treatments substantially decrease the wear rate of the AISI M2 HSS compared to the conventional treated ones. However, the improvement in wear rate by deep cryogenic treatment is significantly higher than that achieved by shallow cryogenic treatment.

Muammer Nalbant *et al.* [20] in his experiment founds cutting condition affects the maximum cutting forces and torque. The maximum cutting force and torque in cryogenic machining are observed to be more than those in dry cutting of about 3.3% to 6.5% and 7.9%. Also Cutting speeds affect the maximum cutting forces and the maximum cutting torque. Cutting forces increase with increasing cutting speed. However, the maximum cutting torque decreases with increasing cutting speed.

Simranpreet Singh Gill [22] in his work shows the effects of cryogenic treatment on M2 HSS turning tools summarizes that the shallow cryogenic and deep cryogenic treatment can significantly enhance the service life of M2 HSS turning tools, however the tools subjected to deep cryogenic treatment stand to gain relatively more as compared with shallow cryogenically treated tools. The recorded maximum tool life enhancement over traditionally heat treated tools in the present study is approximately 35% for shallow cryogenically treated tools and 50% for deep cryogenically treated tools. Also deep cryogenically treated turning tools of M2 HSS perform more consistently as compared to shallow cryogenically treated as well as traditionally heat treated tools.

S. Sendooran *et al.* [23] shows deep cryogenic treatment is a secondary hardening. This deep cryogenic treatment is depends only on temperature not on soaking time. In this process retained austenite structure was completely converted into martensite structure and hardness is improving about 17%.

M.Dhananchezian *et al*. [24] carried out experiments on orthogonal cutting of AISI 1045 steel and Aluminum 6061-T6 alloy under dry and cryogenic conditions. Concluding that cryogenic cooling reduces the cutting temperature by 19 to 40% depending upon the level of process parameters and work material, The influence of cryogenic cooling increases the cutting force to a maximum of 15% and 10% for the machining of AISI 1045 steel and Aluminum 6061-T6 alloy respectively, Cryogenic machining with liquid nitrogen jet reduces the chip thickness up to 25% over dry machining, The shear angle in cryogenic machining was increased up to 30%, From experimental investigation he clears that, the machinability characteristics of AISI 1045 steel and Aluminum 6061-T6 alloy have shown better results in cryogenic machining over dry machining.

CONCLUSION

1. The increase in wear resistance has been attributed to the transformation of soft retained austenite into the harder martensite phase, and the formation of fine carbide particles in the metal structure. These changes are the principal reasons for the dramatic improvement in wear resistance.
2. 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.
3. Cryogenic treatment can reduce the austenite content but cannot make retained austenite transform to martensite completely.
4. The cryogenic treatment process must be performed according to predefined temperature protocols, to ensure the maximum effectiveness; the cryogenic process should be carried out in a dedicated programmable cryogenic system.
5. Cryogenic treatment can increase the cutting forces, which can be reducing by use of secondary liquid nitrogen.

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