The Effects of Cryogenic Treatment on Cutting Tools

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Abstract: Enhancing the cutting tool life is important and economic factor to reduce the tooling as well as manufacturing cost. The tool life is improved considerably by 92\% after cryogenic treatment. The cryogenic treatment is a one-time permanent, sub-zero heat treatment that entirely changes cross-section of cutting tool. The cryogenic treatment is carried out with deep freezing of cutting tool materials to enhance physical and mechanical properties. The cryogenic treatment improves mechanical such as hardness, toughness and tribological properties such as wear resistance, coefficient of friction, surface finish, dimensional stability and stress relief. The deep cryogenic treatment is the most beneficial treatment applied on cutting tools. The cryogenic treatment is the most advanced heat treatment and popular to improve performance of the cutting tool. The optimization of cryogenic treatment variables is necessary to improve tool life. This study reviews the effects of cryogenic treatment on microstructure, tribological properties of tool steels and machining applications of cutting tool by investigating the surface and performing the surface characterization test like SEM. The economy of cutting tool can be achieved by deep cryogenic treatment.

Keywords: Cryogenic treatment, tool steel, tool life, cutting tool, surface characterization, SEM.

I. INTRODUCTION

Metal cutting is an important manufacturing operation in the manufacturing industry. The machining processes are done on work piece to get finished product of required quality [22]. The manufacturing industries are continuously striving to reduce the cutting cost and hence final product cost. The development of cutting tool material is necessary to produce high quality of product with high tolerances of manufactured goods with the required production rate [15].

Cutting tool is important element in any of the manufacturing operation such as drilling, facing, milling, turning and so on. The materials which are used in production of cutting tool should have the different properties such as hot hardness, wear resistance etc. to impart these properties. Conventionally the tool is surface treated by using coating material or heat treated such as to increase the life of the tool at last.

There are mainly three costs associated namely labor cost, material cost, tooling cost for the final product [29]. The material cost and labor cost are varying and increasing, so tooling cost
can be reduced with improved cutting tools performance. The cutting tools performance is improved by surface coating and cryogenic heat treatment. Cutting tool’s life plays an important role in increasing the productivity of machines. The economy of cutting tool depends on the tool life. Thus any improvement in cutting tool performance reduces the cost of production, reduces tool changing time and helps to achieve required production target [17]. The development of new cutting tool with greater productivity and tool materials capable of higher cutting speeds and feed rates is required.

The main applications of tool steels are for broaches, drills, milling cutters, taps etc. The tool life of cutting tools plays an important role in increasing the productivity and tool life is an important factor for economic consideration [26]. Conventional heat treatment of steels produces retained austenite in steel. The austenite is transformed into martensite causes nearly 5% volume expansion resulting in distortion of cutting tools. Cutting tools life is affected by the various factors like depth of cut, feed and cutting speed, material used for cutting tool, heat treatment carried out on cutting tool, work piece material and nature of cutting [31]. The characteristics of a good cutting tool material are abrasion resistance, heat conductivity, hot hardness, impact resistance, strength and wear resistance. Presence of various elements in tool material play important role in deciding these characteristics of cutting tool. Element analysis of cutting tool material by SEM and EDX tests, emerge as novel technique to confirm the characteristics of the cutting tool.

II. CRYOGENIC TREATMENT

The word “Cryogenics” is originated from Greek words – “kryos” means ‘cold’ and “genics” means to ‘generate’. Scientifically, it means that use of materials at sub-zero temperature say -145°C [25]. Cryo-treatment is an inexpensive [13, 32], one time permanent [21, 32], supplementary [13, 18, 23, 27], an add-on-process [32], sub-zero heat treatment affecting entire cross-section of the materials than coatings [10, 14, 15]. Cryogenic treatment is carried out for enhancing the tool life through microstructural changes occurred during cryo-treatment [26]. Cryogenic treatment is applied on alloy steels, tool steels, brake discs, composites, cutting tools, plastics and race car engines. Cryogenic treatment has multiple applications such as aerospace, automotive, aviation, electronic, fertilizers, biomedical (for cooling purposes), nuclear power plants and manufacturing etc.

Cryogenics is defined as the science of producing low temperature environment especially below 0°C [10]. The improvement of tools mainly depends upon selection of heat treatment sequence process properly, cryosoaking time, cooling and heating rate [32]. There are two levels of cryogenic heat treatments given to the materials such as shallow cryo-treatment (-80 to -145 °C), deep cryo-treatment (-145°C and below).

K. S. Mahesh Lohith [17] found that until the end of 1960’s, the idea of cryogenic treatment was attempted by directly immersing metallic components and tools in liquid nitrogen. High brittleness, cracks formed due to thermal shock and volumetric expansion of cryo-treated components was reported in many cases. The advancements in the field of refrigeration cycles was made use by Bush (Cryo Tech, Detroit, MI) in developing CT system towards the end of 1960’s and it was further improved by Paulin with a feedback control system on heating and cooling rates that allowed to perform an effective and crackles cryo-treatment. Application of cryo-treatment on machine tools was investigated by Barron R.F. in 1980’s, and the hardness as well as wear properties of the material showed a positive response and also found that retained
austenite is transformed into martensite and fine precipitates of carbides was the main reason behind it.

Cryogenic treatment involves following operation sequence [10],
1. Slow cooling to predetermined temperature e.g. -145 °C, -196 °C
2. Soaking for predetermined time(4 hours to 48 hours)
3. Slow heating to room temperature
4. Tempering

![Fig. 1 Cryogenic treatment process](image)

![Fig. 2 Cryogenic treatment cycle for SCT tool and DCT tool](image)

Application of cryotreatment on machine tools was investigated by Barron R.F. in 1980’s and the hardness as well as wear properties of the material showed a positive response and also found that transformation of retained austenite and fine precipitates of carbides into martensite was the main reason behind it.

K. Sangeet Raj et al. [10] found that before proceeding to the cryo-treatment, batch of conventionally heat treated samples has to be cleaned to remove impurities, dirt and traces of salt layer found on their surfaces. JiXiong et al. [25], Sitki Akincioglu et al. [5] investigated cryogenic treatment improves tool life of cutting tool, decreases cutting forces and wear of tool, enhances surface roughness, fatigue resistance, ductility. Studies show that cryo-treatment improves abrasive resistance, thermal and electrical conductivity, tool life, hardness, toughness and wear resistance. The gases like helium, neon, nitrogen and oxygen etc. are used for cryo-treatment. Nitrogen constitutes almost nearly 4/5th i.e. 78.03 % of air, so liquid nitrogen gas is easily available. Therefore, liquid nitrogen gas is preferred during cryo-treatment applications abbreviated as LN₂ [10]. The liquid nitrogen gas is colorless and odorless having boiling point of -196 °C and melting point of -210 °C.
III. TOOL STEEL

Tool steel refers to a variety of alloy and carbon steels. Tool steels are particularly used for production of cutting tools. Tool steels are used for cutting tool, dies, and industrial tooling and punches [20]. Tool steels are divided into the six types of categories such as cold work, high speed, hot work, plastic mold, shock resisting, water hardening and special purpose tool steels [12, 20]. Conventional heat treatment on tool steel gives toughness, hardness, wear resistance and ductility to the steel. The cryogenic treatment on tool steel gives better performance in tool life. The literature reveals that cryogenic treatment effects on the tool steel as follows. The Austenite i.e. soft phase of the iron is completely converted into Martensite i.e. hard phase of the iron [21]. The precipitation of fine carbide particles and homogeneous structure of carbides improves mechanical properties such as hardness, toughness, dimensional stability, fatigue resistance, residual stress as well as tribological properties such as coefficient of friction and wear resistance.

IV. EFFECT OF CRYOGENIC TREATMENT ON MECHANICAL AND TRIBOLOGICAL PROPERTIES

The experiments of cryo-treatment are carried out on various tool steels. The cryo-treatment improves mechanical properties such as hardness, toughness and tribological properties such as coefficient of friction and wear resistance. The changes in microstructure occurred as Austenite is completely transformed into Martensite. Precipitation of fine secondary carbide particles and more homogeneous distribution of metal particles, refined homogeneous structure of carbides occurred.

4.1 Wear behavior

The wear of cutting tool causes serious inefficiencies, sudden breakdowns and hence financial losses. These losses can be minimized by the cryogenic treatment on cutting tools. K. Sangeetha Raj [10] states that cryogenic treatment on tools shows increase in wear resistance. The cost benefits of increased wear resistance of cryo-treatment of tooling include:

- Purchase order of new cutting tool is delayed
- Decreased regrinding, reshaped and rework
- Less scheduled downtime to change tooling
- Labor cost lowered
- Decreased loss of production parts when tooling is out of specification
- Ideal time is reduced for replacement of machine parts
- Useful for coated as well as uncoated tool steel
- It gives better electrical and thermal conductivity

Arslan Y. [7] pointed that the best wear resistance is obtained through long soaking time and final tempering process of the punches, Adem Cicek et. al. [9] found in his investigation that the wear resistance of the DCT and DCTT samples was improved by an average of 12% and 24% respectively as compared to the CHT sample for AISI H13 hot-work tool steel. The deep cryogenic treatment transforms retained austenite into martensite and more uniform and homogeneous secondary carbide precipitation.

Candaneet al. [18] found that conventional heat treated showed wear rate as high as 6 times that of deep cryogenic treated specimens. Also it was observed that the coefficient of friction at the
interface between disc and pin was 30 – 55 % lesser in the case of deep cryogenic treated specimen. P. Paulin et al. [34] has shown the differences in wear life between parts cold treated at about −80°C and cryogenically treated at −190°C using liquid nitrogen gas. Shaikh Ather [12] reported that the wear resistance obtained is 18.54 % when the load is 49.6 N whereas the minimum increase in wear resistance is 14.04 % when the load is 24.5 N. It can also be observed that there is a variation in increase of wear resistance along with the variation in load. The average increase in the wear resistance obtained is in around 22.56 %. K. S. Mahesh Lohith [17] investigation reveals the effect of cryotreatment on austenitic D3 tool steel in terms of increase in hardness and enhancement in the wear resistance of the material. They found that enhancement in wear resistance better by 80 % for cryotreated specimen in comparison with untreated specimen and found that the coefficient of friction decreases when austenitic ductile iron type D3 tool Steel for cryotreated specimen.

Y. Arslan [6] mainly speaks about the six types of wear behavior which occurs in punches commonly which are mainly fretting fatigue, cavitation, abrasive, shear, adhesive and diffusion wear. He has briefly studied by comparing the heat treated punches and 36 hr CT, and 2 hr tempered punches (CTT). Figure 3 shows the wear found in 36 CTT due to the phase transformation of austenite to martensite which took place during cryotreatment.

Fig. 3 SEM micrograph of the (a) HT and (b) 36 CTT punches

4.2 Microstructure analysis

Nay Win Khun et al. [3] investigated the microstructures of the AISI D3 samples with different treatments. In Figs. 4 (a) and 4 (b), the microstructure of the RAW exhibits non-uniform distribution of large, elongated white regions of primary chromium carbides and uniform distribution of smaller, nearly spherical secondary chromium carbides. The conventional heat treatment of the AISI D3 sample shows the uniform distribution of primary and secondary chromium carbides and also the reduced the size of the carbides. Which shows the more homogenized carbide distribution and the reduced carbide size in the microstructure of the CHTWOT (Figs. 4 (c) and 4(d)) compared to those in the original microstructure of the RAW (Figs. 4 (a) and 4 (b)). As shown in Figs. 4 (e) and 4 (f), the deep cryogenic treatment of the CHTWOT probably gives rise to the most homogenized carbide distribution and the smallest carbide size in the microstructure among the AISI D3 samples used in this study.
Fig. 4 Optical and SEM images showing microstructures of ((a) and (b)) RAW, ((c) and (d)) CHTWOT and ((e) and (f)) DCTWOT

Fig. 5 SEM images of (a) CHT, (b) DCT and (c) DCTT samples

Adem Cicek [9] has claimed that by DCTT (Deep cryotreated and tempered) the better wear resistance can be obtained as per most of the researchers there are only two main reason which increase the wear properties and hardness of the material which are the phase transformation which takes place during cryogenic i.e from austenite to martensite, and the second is the precipitation of carbides in the matrix finer the carbide particles led to less wear of the tool. In figure 5 (a), (b) and (c) We can observe the DCTT samples have the finer carbide particles than the CHT and DCT samples as the tempering after DCT also relives the internal stresses of the material. N. B. Dhokey[21] states that the cryosoaking is also responsible for the carbide precipitation, the kinetics of carbide Precipitation is directly proportional to the incubation time.

4.3 Machining applications
In recent years, literature study reveals that effect of cryogenic treatment on cutting tools in machining operations like turning, drilling, milling etc. It is found that the cryogenic treatment of cutting tool provides many positive effects in all machining operations including increased tool life and wear resistance along with reduction in cutting force and surface roughness. Reddy
et. al [33] has conducted experiments with machining operations using deep cryotreated and multi-layer CVD-coated tungsten carbide (TiCN, TiN) tools on C45 work piece material and found that decreased cutting force and surface roughness with increase in cutting speed. They have used deep cryotreated tungsten carbide (ISO P-30) cutting tools and microstructure is analyzed. Simranpreet Singh Gill [26] investigated tool life of cryotreated M2 tool steel and study shows that maximum tool life enhancement is approximately 35% for shallow cryotreated tools and 50% for deep cryotreated tools over traditionally heat treated tools. A D Shirbhate [27] used M2 HSS Drills for his investigation and found the 35% reduction in Ra value is observed while comparing non CT tools with CT drills (−185 °C, 24 h), which clearly indicate improvement in surface quality of the work piece. Swarndeep Singh [29] claims in his investigation cryogenic treatment can improve the lifespan of HSS cutting tools. Further it reduces the production cost by controlling tooling cost, and helps to make manufacturing process economical. D. Senthilkumar and I. Rajendran[16] found that the significant parameters for improving the mechanical properties of steel in the following order as soaking temperature (72%), soaking period (24%), rate of cooling (10%) and tempering temperature (2%) and the effect of tempering period is insignificant.

V. CONCLUSION

Significant research work is done on cryogenic treatment of different types of tool steels and punches. The optimization of machining parameters at different cryogenic treatment is done. The cryogenic treatment of tool steels is done and mostly turning and drilling operations are carried out to study effect of cryogenic treatment on different types of tool steels. The optimization of parameters as heat treatment sequence process, cryosoaking temperature, cryosoaking time, cooling and heating rate etc. should be done in future work to improve cutting tool performance at maximum efficiency. The conclusions of the review study are as follows:

- Cryogenic treatment is a supplementary subzero heat treatment and an add-on-process which affects entire cross-section of the tool material.
- Cryogenic treatment is used to enhance the performance of cutting tool.
- There are two types of cryogenic treatment are done on tool steels namely as shallow cryotretment at −80 °C to -145 °C and deep cryotretment at below -145 °C. Both treatments are beneficial for different cutting tool type and tool materials.
- The improvement of cutting tools mainly depends upon proper selection of heat treatment sequence process, cryosoaking temperature, cryosoaking time, cooling and heating rate etc.
- The sequence of complete process of cryogenic heat treatment is austenizing, quenching, cryogenic treatment and tempering.
- For better results of cutting tools, cryogenic treatment should be carried out after quenching and before tempering.
- The deep cryogenic treatment is more beneficial than shallow cryogenic treatment.
- Cutting forces are decreased and surface roughness is improved, so machining at higher cutting speed is possible of cryotreated tools.
- SEM graphs reveal that after cryogenic treatment, austenite is completely transformed into martensite and precipitation of fine carbide particles; these two phenomenons are
useful to improve mechanical and tribological properties of tool steel. Also better corrosion resistance, high thermal conductivity is achieved.

- Optimization of cutting tool performance and reduction in cutting tool cost is necessary for the economy of cutting tool.

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