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A REVIEW ON EFFECT OF CRYOGENIC TREATMENT ON HSS AND CARBIDE TOOLS

Jadhav Bhavesh N[1], Gawad Harsh A[2], Jha Sumit B[3], Lakhani Mansi[4]

[1]*Mechanical Engineering*, Viva Institute of Technology
[2] *Mechanical Engineering*, Viva Institute of Technology
[3] *Mechanical Engineering*, Viva Institute of Technology

Abstract —*Every time when it comes to machining process or specifically metal removal processes improving the performance of cutting tools is an important factor in reducing production costs. Cutting tools are subjected to different processes such as treatments and coating in order to improve their performance. Recently cryogenic Treatment is The paper presents the ideology and methodology for improving the life of cutting tools using the technique called Cryogenic treatment. Paper presents the effect of cryogenic treatment on various properties and performance of cutting tools. The review also takes into considerations various parameters of cryogenic treatment that affect the performance of cutting tool*

Keywords- *Cryogenic treatment, tool wear, tool life, HSS tool, carbide tool.*

I. INTRODUCTION

Metal cutting or simply a machining process is one of the oldest methods of making any products or shaping work pieces in manufacturing industry. It is estimated that approximately 15-20 % of all manufactured components is made by metal cutting process. Currently, in the modern world the need of perfection in any product is increasing rapidly. Due to which the needs and interest in high speed and high precision machining is increasing. As a result of which the need of improvement in high speed tools is needed even before the development of high speed machinery.
Hence researchers are increasing in finding the techniques of improving the various properties such as tool life, corrosion resistance etc. of cutting tools. The increase in properties of tools will not only reduce cost of overall machining but also will increase the quality of finished products.The various methods developed to improve various properties of cuttings tools have been discussed below:

1.1 HEAT TREATMENT

Along with the development of new manufacturing methods and technologies there is also increase in treatment of cutting tools for better results. A common treatment will not solve problem of all tool application, the particular treatment or method should be provided depending on applications of tools.
In the overall sense, heat treatment may be defined as an operation or combination of operations involving the heating and cooling of a metal or alloy to get preferred properties. Heat-treating processes consist of exposing a metal to a definite time-temperature cycle, which may be divided into three parts.[1]
(1) Heating,
(2) Holding at temperature (soaking), and
(3) Cooling.[1]
The rate of heating is not mainly important unless a material is in a greatly stressed condition, such as is imparted by severe cold working or prior hardening. The object of holding a material at heat-treating temperature is to assure consistency of temperature throughout its whole volume. The rate of heating of thin specimen is not as same as the thick specimen, if different thicknesses exist in the same piece, the period required to heat the thickest section uniformly governs the time at temperature.[1]
The structure and properties of a material depend upon its rate of cooling and this, in turn, is governed by such factors as mass, quenching media, etc. It must be realized that the thicker the section, the slower will be the rate of cooling regardless of the method of cooling used.
The main disadvantage of heat treatment is that it does not completely convert austenite into martensite. This martensite formed is known as primary martensite, which is brittle. It should be treated to reduce this brittleness. To obtain the desired steel properties, it is recommended by most researchers to execute cryogenic treatment after completion of conventional heat treatment process, some also suggest cryogenic treatment before tempering too.
Cryogenic treatment is a low-cost permanent treatment which follows the conventional heat treatment cycle. Research studies shows that cryogenic treatment is proved to be an effective method for improving life of tool along with other mechanical properties.[3,4,5]

II. CRYOGENIC TREATMENT

Cryogenic Treatment is the process of cooling a material to temperatures extremely below room temperature. The method of processing materials at subzero temperatures was first acknowledged when metal parts that were transported via train were mixed with dry ice (at −79°C), resulting in observable increases in wear resistance. Later research work was carried out to find out the change in properties first by dry ice (−79°C) and then by using liquid nitrogen (−196°C).[1,2]Research shows that thecryogenictreatment is an effective method that enhances the tool life and wears resistance of cutting tools.[1,,3,4,5]

Studies shows that there is a significant increase in various properties like hardness, toughness, wear resistance, tool life, and abrasive resistance of cutting tools after cryogenic treatment as compared to untreated tools. Various parameters are taking into considerations for performing the cryogenic treatment. Factors that affect the change in properties of tools include cooling period, soaking time, final soaking temperature, rate of cooling, rate of tempering process and type of tool etc. Hence to achieve best result proper cryogenic treatment differs for tool to tool and material to material. Therefore there is requirement of study of cryogenic treatment on different materials.[4,5]

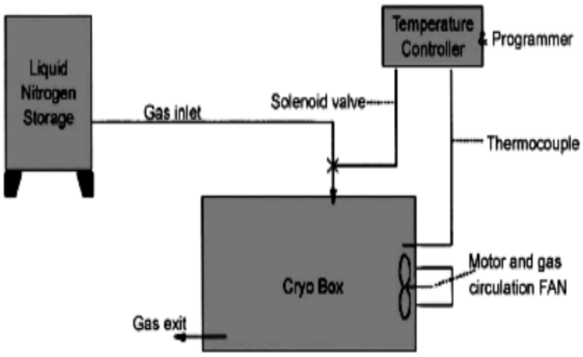
Although cryogenic treatment cryogenic treatment was first developed around a century ago, there are no specific standards that how much the tool is to be treated and at what rate of cooling. Different researchers are working on how rate of cooling affects the properties of materials and trying to find out optimal factors for a particular tool.

Cryogenic Treatment is not, as it is often mistaken for a replacement for heat treatment, rather it is an add-on or auxiliary process to conventional heat treatment to be done before tempering. However, it has been reported that some enhancement can be obtained by carrying out the treatment at the end of the standard heat treatment cycle, i.e. on the finished tools.[4]

A essential peculiarity among different Cryogenic Treatment is given by the parameters of the cooling-warming cycle in two types depending on the minimum temperature reached during the cycle and are categorized as:

- Shallow Cryogenic Treatment (SCT) or Subzero Treatment: the samples are placed in a freezer at 193K and gradually warmed to room temperature.[6]
- Deep Cryogenic Treatment (DCT): the samples are slowly cooled to 77K, held-down for many hours and then gradually warmed to room temperature slowly.[6]

Figure below shows the schematic setup for cryogenic equipment. It comprises of an insulated box with a motor with acirculating fan to circulate the temperature effectively, one thermocouple to measure the cryogenic temperature inside the box which is connected to a temperaturecontroller and programmer circuit, a liquid nitrogen tank and a solenoid valve for the gas inlet.[6]The DCT treatment begins with slowly cooling the specimens in the cryo box to a cryogenic temperature of approximately 77Kusing cryogenic fluids such as LN_2 (Liquid Nitrogen).The temperature inside the cryo box is maintained using temperature control setup along with solenoid valve and fan is used to circulate the temperature uniformly. Later, after attaining the required temperature it being hold at that temperature for a nearby 24 hours (Holding time changes according to the requirements and differ from study to study). Later the specimens are brought back to room temperature slowly. The cooling rate and Heat up rate also affects the properties change of the specimens. Lastly the specimens i.e. cutting tools are goes under tempering process upto approximately 473K so as remove internal stress if induced during cooling process.



"Figure I- Setup of Cryogenic Treatment".[6]

III. PARAMETERS EFFECTING THE RESULT OF CRYOGENIC TREATMENT

Darwin et al.[7] studied the key parameters involved in cryogenic treatment for change in properties of different materials as: cooling rate, soaking temperature, soaking time, heating rate, tempering temperature and tempering period. Cooling rate can be defined as the rate at which the sample is cooled to the soaking temperature. Soaking temperature is termed as the temperature at which the sample is kept, while the soaking period can be termed as the time for which the sample is held at the soaking temperature. The heating rate is defined as the rate at which the sample is gradually heated back to room temperature. Their results show that the importance of the parameters for improving mechanical properties of steel in the following order of importance.[7]

- Soaking temperature (72%)
- Soaking period (23%)
- Rate of cooling (10%)
- Tempering temperature (2%).[7]

3.1 Rate of Cooling

A typical cryogenic treatment can be done by two types. First method is direct approach in which the specimens are directly brought down to cryogenic temperature.[21,24] The main problems associated with direct approach is that, cracks are generated due to thermal shock, and rapid change in temperature although some studies shows the improvement in properties using this technique. The other method is gradual approach, in this method the specimens are gradually cooled down to a cryogenic temperature in a certain period of time. The rate of cooling in this method generally varies from 0.5℃/ min to 1.5℃/ min.[17]

3.2 Soaking Period

Molinari et al.[8]after studying different researchers of different period of soaking recommended that the maximum soaking period shouldnot be more than 35 h; as prolonged period do nothave any significant effect. Also cooling rate must not exceed 20-30°C/hr. in order to prevent material from cooling stress. In two independent studies by Barron RK.[9] and Dobbins DB.[10], suggested 20h as enough soaking time for atoms to overcome various defects in a material and to stabilize on new locations.

There are many studies which show many different minimum soaking temperatures, but most of these research works have most temperature under range of 24-48 hrs. Hence more research must be carried out in order to find more specific period. Although the soaking period also varies from material to material and application to application and also minimum temperature to be achieved.

However, Kalsi.[11] suggested that slow rate of loweringdown to the lowest most temperature would be helpful toachieve maximum improvement in wear properties and toavoid any microcracking; the value may be to 0.5°C/min.

3.3 Soaking Temperature

Bensely et al.[12]studied two types of cryoprocessing shallow cryogenic treatment (193 K) and deep cryogenic treatment (77 K), as a supplement to conventional heat treatment. The amount of retained austenite in conventionally heat treated and untampered specimen which was found to be 28.1 ± 3.5% was reduced to 22± 7.6%, and 14.9 ± 5.8% in shallow cryogenically treated, and deep cryogenically treated samples respectively whereas almost same changes were observed for tempered specimens.

Reddy et al.[11] have also concluded that the life of P-30 tool insert increases by 10% when treated at −96℃ (177K) and 20.8% when treated at −175℃ (98K).[11]

Gu et al.[13] carried out similar studies. Studies were conducted to investigate the effect of cryogenic treatment temperature on the hardness of Ti–6Al–4V alloy and found that deep cryogenic treatment (−196 °C) was the most effective parameter on the hardness of the alloy. Theseincreases are mainly caused by the increase of dislocation density and twins and due to the slow movement of atoms in cryogenic temperature.

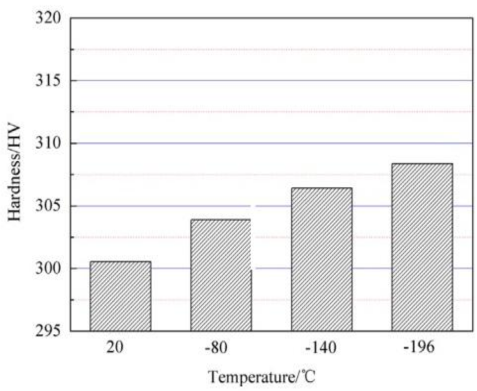


***Fig II: - Variations of hardness at different cryogenic treatment soaking temperatures.*[13]**

Babu P.S et al.[14]conducted experiments on wear resistance of M1, H13 and E19 steel. The experiments were at various temperatures ranging from 273 K to 83. Results concluded that there is improvement in wear resistance of material of about 3.2 to 3.8 times. Their result also says that soaking temperature plays a vital role in improving various properties of materials.

3.4 Warming and Tempering Stage

After soaking the specimen for specific time they are ramp up to the room temperature. The ramp up cycle is very important to the process. If the specimen is ramped up too fast it may cause generation of various defects in the specimen. For example consider the ice block poured in the hot water, the ice cube breaks due to generation of crack due to sudden change in temperature. Same happens if specimen ramp up rate is very high.

Cutting tools are generally undergoes tempering process after the cryogenic treatment. The main aim of performing tempering process to reduce internal stresses on the cutting tool that occur due to excessive cooling.

The cryogenic treatment coverts retained austenite into martensite. But the martensite converted is primary martensite, which will be brittle. Hence tempering process is done to remove brittleness.[31]

IV. INFLUENCE OF CRYOGENIC TREATENT ON PROPERTIES OF TOOL

4.1. Wear and Wear Resistance

The main reasons for the development of cryogenic treatmentwere rapid wear of tools while machining. Cryogenic treatmentwas first seen as a process of increasing wear resistance andtool life of a tool.

Yong et al.[15] conducted the preliminary test to determine thecontrol of cryogenic treatment on end mills, zone punches,lathe tools, and concluded that an increase in tool life from50% to more than 200% were observed for the tools whichhad been soaked in liquid nitrogen for 12 hours.

Rupinder and Kalmajit Singh.[32] studied the wear resistance by evaluating the results obtained by performing pin-on-disc wear tests at different loads using constant speed on AISI M2 HSS tool.The results obtained from the wear tests performed are presented in Table I. The results shows that there is significant increase in wear resistance of deep cryogenic treatment tool when compared to shallow cryogenic treatment and untreated. The increase in wear resistance at load of 49 N was 24.26% when compared to untreated specimen and was 18.75% when compared to shallow cryogenic treated.

***Table I: - Tribological characteristics of AISI M2 HSS for Pin-on-Disc wear tests at 1.5 m/s velocity*.[32]**

Type of Heat Treatment	Normal Load, N	Mean Weight Loss ,g	Wear Rate, Wr × 10-4 mm3 / Nm	Wear Resistance Improvement w.r.t. CQT,%	Wear Resistance Improvement w.r.t. SCT,%
Untreated	49.0	0.081	0.338	--	--
	68.6	0.194	0.577	--	--
	88.2	0.303	0.702	--	--
Shallow Cryogenic Treated	49.0	0.059	0.256	24.26	--
	68.6	0.117	0.348	39.68	--
	88.2	0.19	0.460	34.47	--
Deep Cryogenic Treated	49.0	0.050	0.208	38.46	18.75
	68.6	0.086	0.256	55.63	26.43
	88.2	0.127	0.294	58.11	36.08

Das et al.[17] investigated the correlation of wear behavior and hardness of AISID2 steel. The shallow cryogenic treatment in comparison to conventional heat treatment enhances the bulk hardness by just 3.8% but reduces the wear rate by 35.8% at normal load of 78.5 N. Similarly, the difference of bulk hardness between shallow cryogenically treated and deep cryogenically treated samples is marginal which was around 4.2%.

Yong et al.[18] reported the increase in wear resistance of YG8 Tungsten carbide inserts which were cryogenic treated to non-treaded tool and resulted in decrease in wear resistance factor ΔG from 6.41 to 4.02 which is the ratio of Δm is the mass loss of YG8 inserts and ΔM is the corresponding loss of diamond. Gill et al used readily available TiAlN coated square shaped tungsten carbide inserts (P25) and were cryogenically treated at two levels i.e. DCT at -196*℃* and SCT at -110*℃*. The results concluded that wear resistance were highly increased of cryogenically treated tool when compared to untreated tool at low cutting speed but at high cutting speed the increase in wear resistance was not much significant and the results of SCT and DCT were almost nearby.

4.2. Tensile Strength

Xiong et al.[19] reported thatthe elongation, ultimate tensile strength and the yield strength of the cryogenic treated magnesium alloy added with zirconium have been changed from 298 MPa, 370 MPa to 460MPa, 510 MPa and 8.5% which means it has improved by 57%, 38% and 280% respectively, as compared to those of the same alloy without cryogenic treatment. Baldissera and Delprete.[20] reported that the tensile test results of 18NiCrMo5 carburized steel shows a significant hardness improvement of 0.6 HRC and leads to a notable increase of the ultimate tensile strength approximately +11% by performing the deep cryogenic treatment after the tempering.

Yong et al.[18] reported hardness and compression strength of the YG8 samples that were cryogenic environment are higher than that of the untreated ones, while bending strength and toughness show no significant changes. The improvement of mechanical properties is highly dependent on the soaking time. Because increase of soaking time from 8 to 24 hrs increases hardness from 1625 HV to 1650 HV but when soaking time was increased to 72 hrs the hardness were changed to 1648 HV

4.3. HARDNESS

Hardness testing is broadly used for material valuation due to its simplicity and also because of its low cost relative to direct measurement of many properties. Hardness testing does not give a direct measurement of any performance properties, but it correlates with various mechanical properties like wear resistance and material strength.

R. Mahmudi et al.[22] studied the influence of cryogenic treatment on the wear behavior and mechanical propertiesof high-speed steel M2. They concluded that deep cryogenic treatment improves hardness and wear resistance due to the transformation of retained austenite into martensite and also some precipitation of eta-carbide particles.

D. Candane.[23] studied the effect of cryogenic treatment on M35 HSS and concluded that there is slight increase in hardness of HSS after shallow and deep cryogenic treatment. The change in Hardness is shown in table.

Table II: - Effect of treatment on hardness. [23]

SI. No	CHT	SCT	DCT
HRC	64	64.5	65.5
Vickers Hardness	920	934	980

V. MICROSTRUCTURAL STUDY

Microstructural study help in identifying the key reasons for improvement or changes of properties of any materials. The microstructures of the CHT (Conventionally Heat treated), SCT (Shallow cryogenically treated), and DCT (Deep cryogenically treated) AISI M2 HSS is shown in fig below:[34]

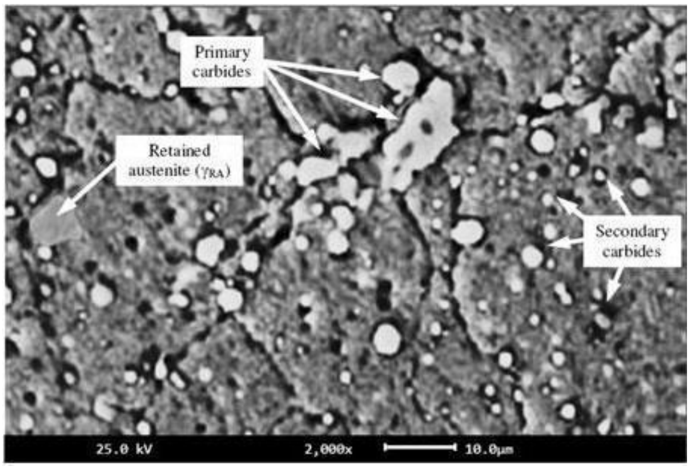


Fig III(a): - SEM images of CHT. [34]

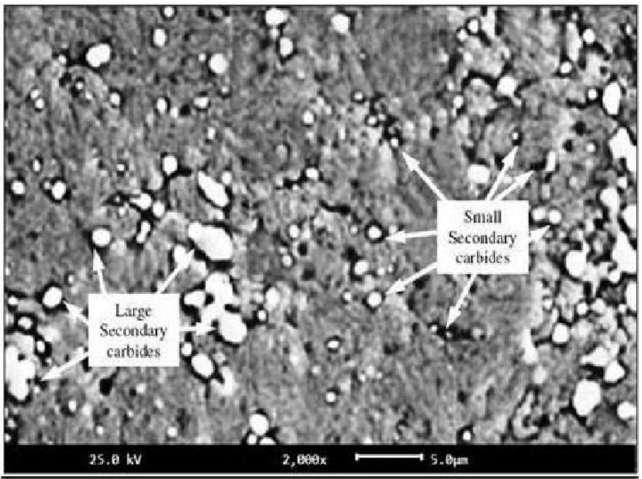


Fig III(b): - SEM images of SCT. [34]

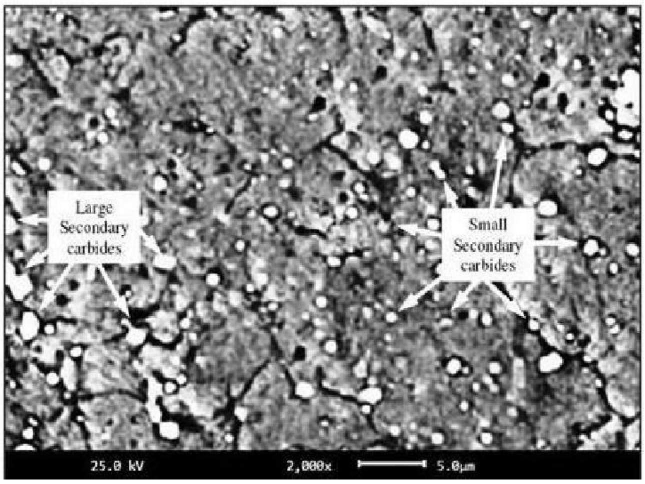


Fig III(c): - SEM images of DCT. [34]

It is clear from microstructures of CHT specimen (Fig.III.a) that primary carbide of somewhat dendrite structure exists in the form of clusters along with secondary carbides though the later are less in number. Some traces of retained austenite can also be seen in the microstructure of CHT.[34]

The microstructure of SCT specimen (Fig.III.b) shows secondary carbides which had been precipitated out during the shallow cryogenic treatment. As evident from the (Fig.III.b), the newly precipitated out secondary carbides can be classified in two categories as large secondary carbides (>4 lm) and small secondary carbides (<4 lm) on the basis of their size. The newly formed carbides are not evenly distributed all over the surface. Also the traces of retained austenite is also reduced.[34]

In contrary to microstructure of SCT specimen, the microstructure of DCT specimen (Fig.III.c) reveals the presence of secondary carbides which are evenly distributed in entire bulk of material. Also, the number of small secondary particles is enhanced after deep cryogenic treatment as compared to shallow cryogenic treatment. It is interesting to note that the retained austenite was almost completely converted into martensite after subjecting the specimen to deep cryogenic treatment.[34]

VI. EFFECT ON CRYOGENIC TREATMENT OF CUTTING TOOLS

5.1 Tool Steel

Singh LP and Singh J.[24]study shows that the wear resistance and tool life of the cryogenically treated is higher compared to those of the untreated HSS at high cutting speeds. Also, cryogenic treatment results in significant enhancement of the resistance to chipping at all cutting speeds.

N.R Dhar.[25] conducted an experiment on AISI 1060 steel at industrial speed-feed combinations, the cryogenically cooled tool steel shows significant variation is properties. The result indicates substantial benefit of cryogenic cooling on surface finish, dimensional deviation and tool life. This may be recognized to mainly reduction in tool tip temperature and favourable change in the chip tool contact.

Dhokey et al.[33] examine the AISI M2 to study the mechanical and metallurgical characteristics considering carbide precipitation of cryogenic treatment for different holding time ranging from 16 to 48 hrs. Results shows high carbide density with low residual stress at soking period of 16 hrs. This was because of carbide precipitation during warming stage that resulted in stress relaxation of matrix.

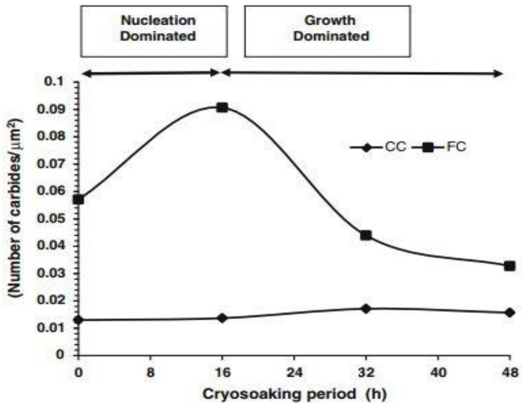


Figure IV: - Variations of fine carbide (FC) density and coarse carbide (CC) density as function of soaking period.[33]

The hardness of AISI M2 HSS rises by 7.76% after exposing the material to cryogenic treatment. For each material there existsan optimum temperature of cryogenic treatment which depends upon the microstructure of material.The primary reason for increase in hardness of AISI M2 HSS is conversion of soft austenite into relatively hard martensite.Refinement and uniformly distribution of secondary carbides also contribute in growing hardness but at significantly lesser extent.[23]

5.2 Tungsten Carbide

Yong et al.[26] studied and observed the improvement of tool life of 9.58% and 21.8% in shallow and deep cryogenically treated milling tungsten carbide inserts. In anotherstudy Seah et al.[27] concluded the changes in cobalt bounded tungsten carbide (Co-WC) and found increase in tool life by 1.5% at high cutting speed by cryogenic treatment. Arner et al.[28]studied five different types ofcryogenically treated tungsten carbide inserts and result showed very consistent changes in entire tool life; Although, the amount of improvement was dependent on various types of tool style.

Gill et al.[29] performed experiments on C60 steel with carbide inserts. They found increase in tool life under both wet and dry condition and also concluded that tool life and wear resistance is highly dependent on cutting speeds too. The recorded increase in tool life was found to be around 55%.

Yong et al.[15] agreed that cryogenic treatment on tungsten carbide tool not only improves the flank wear resistance but also increases resistance to chipping of tools during turning process. Stewart et al.[30] successfully recorded reduction in tool force on cryogenic treated C2 tungsten carbide inserts while turning when compared to non-treated carbide inserts therefore enhancing the life of inserts.

VII. CONCLUSION

From extensive literature survey and review it has been observed that the cryogenic treatment has got potential to improve the mechanical properties of cutting tools and main things that can be concluded are as follows

- Cryogenic treatment is not an alternative to heat treatment but it is an add-on to conventional heat treatment to be carried cot to enhance properties of materials.
- Tempering should be followed by cryoprocessing. Untempered tool materials have surface cracks, which is not beneficial to the life of cutting tools.
- Cryogenic systems allow controlling important cycle parameters such as cooling rate, soaking time and soaking temperature. The choice of optimal treatment parameters requires specific investigation on each material.
- The main properties that are affected are hardness and wear resistance. According to little research work other improved properties are tensile strength, toughness, corrosion resistance etc.
- Although few work shows there is not much increase in impact resistance and tensile strength.
- With a better understanding of this process a wider acceptance of DCT is possible. Researchers must focus their efforts for complete understanding of the mechanisms behind the formation of the ultra-fine carbides precipitation.
- Optimization of tool performance and reduction of the cost of tools can be achieved by using different cryogenic process parameters when necessary in order to determine the effect of the cryogenic process.
- HSS and Carbide cutting tools shows significant improvement in properties when they are cryogenically treated. Hence this method is an effective method for property enhancement of cutting tools.

VIII. ACKNOWLEDGEMENT

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