

A Review on Effect of Cryogenic Treatment on Different Grades of Steel

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ABSTRACT: Different grades of steel with its wide range of application continuously demands for methods to improve properties of steel. General method used to enhance properties of different grades of steel is heat treatment process. Conventional heat treatment process of hardening and tempering and surface treatment processes like carburizing, nitriding etc. are widely used to enhance properties like hardness, toughness, wear resistance etc. for various grades of steel. In conventional hardening process of heat treatment, 100 % conversion of austenite to martensite structure doesn't take place at room temperature. Some amount of austenite remains in the matrix of martensite even after hardening process and is called as retained austenite. Retained austenite in the matrix of martensite results in internal stress within the structure and also limits the enhancement of properties of steel. One of the potential solutions to convert almost entire austenite to martensite and to enhance properties of steel is cryogenic treatment of steel. Cryogenic treatment is not the substitute but the supplementary process to conventional heat treatment properties. Cryogenic treatment is always done after conventional hardening process, wherein hardened material is further cooled till cryogenic temperatures which may range from -80°C to -196°C Cryogenic treatment process results in conversion of retained austenite to martensite and also refines the grain structure of steel which results in enhancement of properties of steel. This paper aims at reviewing the effect of cryogenic treatment on properties of tool steel, alloy steel, plain carbon steel and stainless steel. The study also reviews various parameters of cryogenic treatment that affects the final results of cryogenic treatment process.

KEYWORDS: Cryogenic treatment, Heat treatment, Tool steel, Alloy steel, Plain carbon steel, Stainless steel, Wear resistance, Hardness, Tensile strength, Tensile toughness, Impact strength, Microstructure, Tool life.

I. INTRODUCTION

Steel finds wide range of applications in various industrial sectors. Heat treatment of steel is the most important parameter that affects properties of various grades of steel. Hardening and tempering heat treatment imparts properties of hardness, wear resistance, toughness to different grades of steel such as plain carbon steel, alloy steel, tool steel etc. One of the reason that limits the property enhancement tendency of hardening and tempering is that 100% austenite is not converted into martensite during quenching in hardening process. This results in entrapment of austenite in matrix of martensite at room temperature known as retained austenite. Retained austenite causes significant changes in mechanical properties, such as internal stresses that weaken the part.

Recently, cryogenic treatment of steel is been widely accepted as a supplement process to conventional heat treatment that can aid in almost complete transformation of austenite to martensite with some other microstructural changes that enhances properties of steel[1]

Cryogenic treatment is a supplementary process to conventional heat treatment, and is done after hardening and before tempering of steel[2] [3]. It involves deep freezing of materials at cryogenic temperatures. The process of cryogenic treatment involves cooling the material upto cryogenic temperatures at a constant cooling rate (known as ramp down rate), holding the material at that temperature for specific time (known as soaking period), then bringing the material back to the room temperature at constant heating rate (known as ramp up rate). Soaking temperature, soaking period,

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ramp down rate and ramp up rate are parameters of the cryogenic treatment that affects the output of the treatment[4]. Fig. 1 shows typical cycle of cryogenic treatment.

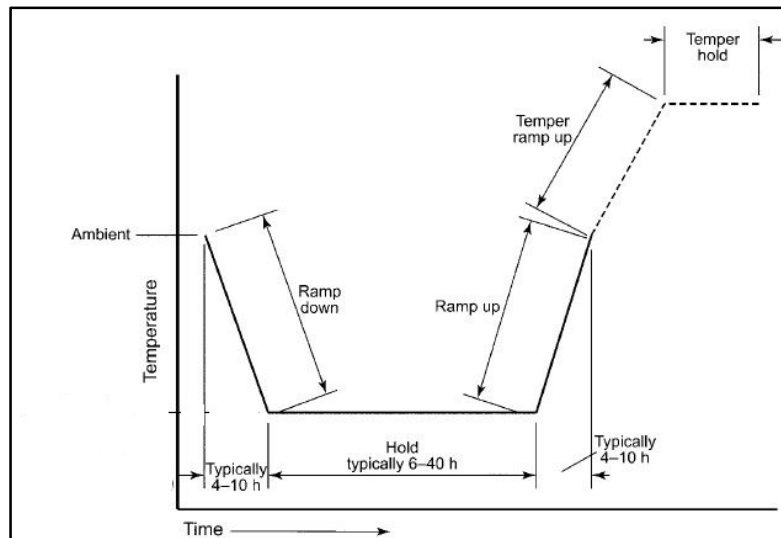


Fig.1. Time – temperature plot for general cryogenic treatment process [4]

Cryogenic treatment can be broadly classified as Shallow cryogenic treatment and deep cryogenic treatment. In case of shallow cryogenic treatment the optimal treating temperature is around 80°C , holding time varies between 5 hours to 8 hours. Also, there is not any specified ramp up and ramp down rate in shallow cryogenic treatment. Deep cryogenic treatment consists of treating temperature around -196°C with the holding time between 16 hours to 48 hours. Also, in case of DCT uniform ramp up and ramp down rate is maintained [5].

Most of the cryogenic treatment cycles have been developed empirically and the treatment shows different results for different materials. The result also varies with variation in parameters off cryogenic treatment. The paper aims at reviewing the influence of cryogenic treatment on different grades of steel.

II. EFFECT OF CRYOGENIC TREATMENT ON TOOL STEEL

A. Molinari et al [6], studied the effect of deep cryogenic treatment on mechanical properties of tool steel by means of both field test and laboratory test. The field test was carried out on deep cryogenically treated HSS tool to evaluate the performance of tool in actual working condition for long period of time to get reliable data. Some of the tools used were cold forming and HSS drill. The cooling rate for reaching the cryogenic temperature of -196°C did not exceed $20\text{-}30^{\circ}\text{C}/\text{hour}$. The soaking time at cryogenic temperature was 35 hours. Total time of test was 100 hours. The block diagram of the set up used for cryogenic treatment is as shown in fig.2.

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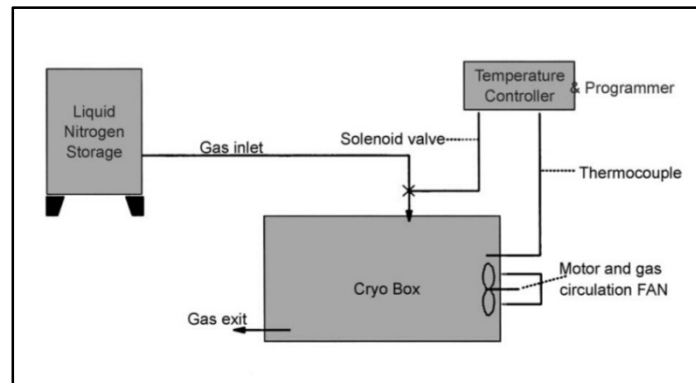


Fig. 2 Block diagram of cryogenic treatment set up.

DCT showed improvement in hardness and hardness homogeneity. Also, the tool consumption was reduced and hence there was 50% of reduction in cost. Along with field test, laboratory test were also carried out on two different grades of tool steel, AISI M2 and AISI H13. After DCT, there was improved wear resistance in AISI M2 steel which can be due to improved hardness. In case of AISI H13 tool material, the wear resistance improved due to enhanced toughness. D Mohan Lal et al [7], studied the improvement in wear in tool steel and die steel due to cryogenic treatment and also studied different parameters of treatment that affects the output of the treatment. The material considered in the study was T1, M2 and D3 grades of steel. Samples made from above materials were treated in different conditions to evaluate the effect of different conditions on wear behaviour. Few samples were conventionally hardened and tempered, others were cryogenic treated post hardening but before tempering. Few were cryogenic treated post hardening and tempering. The different cryogenic temperatures at which the materials were treated are 93K, 133K and 166K. Also, few samples were coated with TiN through physical vapour deposition technique and few samples were cryogenic treated after TiN coating. In the study it was also emphasised on the point that as literature shows that cryogenic treatment is effective on materials other than steel, hence the transformation of retained austenite to martensite cannot be the only underlying mechanism. To study another underlying important mechanism behind the treatment, one of the objectives of the study was avoid the content of retained austenite. For avoiding retained austenite, during heat treatment lower austenising temperature range was selected and the absence of retained austenite was confirmed by examination through X-ray diffraction pattern. After carrying out treatments in various conditions, the wear behaviour of the samples were tested by sliding wear test and flank wear test. The study concluded that the effect of cryogenic treatment is significant when followed by hardening and done before tempering. The life of tool improved by 3%, 10% and 10.6% in material T1, M2 and D3 respectively. Cryogenic treatment post tempering doesn't yield any significant improvement. Cryogenic treatment was not only found more effective than conventional treatment but was also found superior than TiN coating. Also, there was no improvement found when TiN coated material was treated cryogenic treated. The study also suggested that the improvement in the wear properties is primarily based on isothermal process.

J.Y. Huang et al [8], carried out the cryogenic treatment of M2 tool steel to study the changes in microstructure that occurs after cryogenic treatment. In the study conventional heat treatment process started with heating upto austenizing temperature of 1100°C holding for 1 hour and followed by quenching till ambient temperature in cool nitrogen gas. The cryogenic treatment was performed by soaking the sample in liquid nitrogen for 1 week and followed by tempering at 200°C for 24 hours. Tempering was carried for both cryogenic treated and untreated sample. The samples were observed under transmission electron microscope. After the microscopic examination of cryogenic treated and untreated samples it was concluded that, cryogenic treatment not only facilitate carbide formation and increase the carbide population and volume fraction in martensite matrix but also make carbide distribution more homogeneous as shown on fig.3

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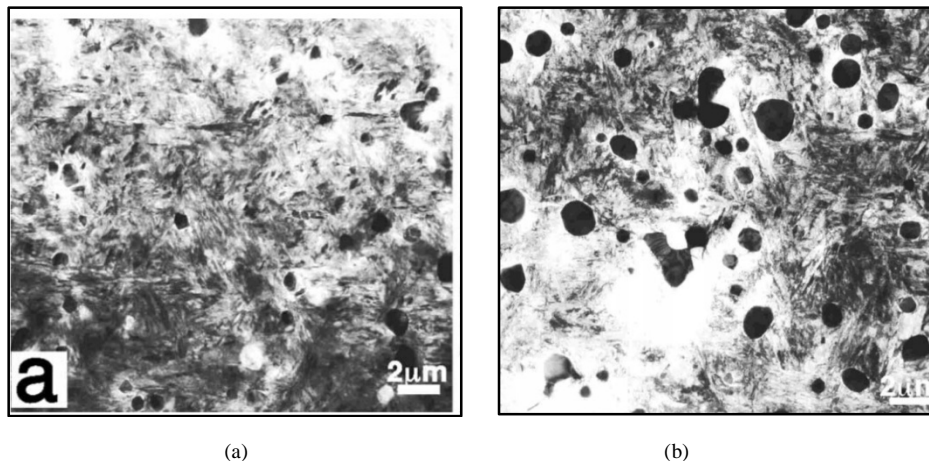


Fig. 3. TEM micrographs (a) Non cryogenic treated specimen (b) Cryogenic treated specimen

They also confirmed that their results were consistent with previous studies that show increase in carbide density and volume fraction, being reason for improved wear resistance property of tool steel. Fig. 3 shows TEM micrographs of non cryogenic treated and cryogenic treated specimen.

As the studies carried out in the field of cryogenic treatment on cutting tool steel resulted in positive impact on properties of tool steel, more research were carried based on application of tool steel for various cutting tools and machining process.

F.J. da Silva et al. [9], carried out cryogenic treatment on lathe tool, twist drill and milling cutter. Lathe tool and twist drill were tested in laboratory post cryogenic treatment and shop floor test was performed for milling cutter. The cryogenic treatment was carried out at -196°C with two different hold times of 24 and 48 hours and at the end triple tempering was carried out at 560°C . The material of lathe tool and twist drill was SAE M2 HSS. For evaluating the effects of cryogenic treatment on lathe tool, the test carried out were microstructural analysis, Brandsma rapid facing test and sliding abrasion test. For twist drill, tool life test was carried out by comparing number of holes machined till catastrophic failure of twist drill at different cutting speeds. Shop floor test for milling cutter was carried out by machining 200 workpieces in industrial environment by both untreated and cryogenically treated milling cutter. The milling cutter material was SAE M2 HSS and was coated by TiN. The conclusions drawn from various tests carried out on cryogenic treated and non-cryogenic treated tools were that the hardness of cryogenic treated tools didn't show much significant change as compared with non-cryogenic treated tools, whereas the percentage retained austenite almost reached to zero as compared to 25% in volume in non-cryogenic treated tool. Superior performance was observed in cryogenic treated tool during Brandsma rapid facing test whereas there was no significant difference found in cryogenic and non-cryogenic treated tool during sliding abrasion test. This phenomenon could be due to ability of retained austenite in non-treated tool to harden during plastic deformation which could be compensated by carbide precipitation in cryogenic treated tools. In case of twist drill, the tool life of cryogenic treated tool increase from 65% to 343% depending on different cutting conditions. On the other hand, the cryogenic treated coated milling cutters showed worst performance when compared with non cryogenic treated coated milling cutter. This behaviour could conclude that cryogenic treatment is not effective on coated materials, as also observed by D Mohan Lal et al,[7] in his study.

V. Firouzdor et al. [10], performed cryogenic treatment on HSS drills, drills were divided into three categories reference drills with no extra treatment, cryogenic-treated drills and cryogenic with a 1h temper at 200°C treated drills. Cryogenic treatment was performed by cooling the HSS drill by cooling it till temperature of -196°C with a hold time of 24 hours and then bringing it back to room temperature at a constant heating/cooling rate of $0.5^{\circ}\text{C}/\text{min}$. For evaluating the performance, drill test was performed by each tool by drilling blind holes in CK40 carbon steel blocks.

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Tool life was specified by number of holes drill until the catastrophic failure of drill occurred. The treatment resulted in increase in tool life approximately 77% in Cryogenic Treated drills whereas an improvement of about 126% in tool life of Cryogenic treated and tempered drills as compared with non cryogenic treated tool. This was due to improvement of wear resistance property of drills post cryogenic treatment. Also, tempering process followed by cryogenic treatment was found to be more beneficial. Mechanical and diffusion wear were two wear mechanism being responsible for tool wear. Out of which diffusion wear contributed more towards tool wear as observed by SEM analysis and chemical analysis of chips. Carbide precipitation is found to be the main reason for improved wear resistance. Conversion of retained austenite to martensite is also one reason for improving wear resistance. The important advantage concluded was that, cryogenic treatment effects entire section unlike coatings of tool, therefore every regrinding gives same tool life.

As cryogenic treatment holds a great potential in enhancing the properties of tool steel, various studies regarding the optimization of parameters of the treatment is also been done. Operational factors of cryogenic treatment like cooling rate, soaking temperature, soaking time, heating rate, tempering temperature, tempering time are said to have direct impact on the results of cryogenic treatment.

M. C. Kumar et al. [11], in their work of optimizing the working parameters of cryogenic treatment have used four iterations of taguchi method to arrive at the optimum parameter of cryogenic treatment. In the study, the parameters considered and their respective four levels are as shown in table 1.

Table 1: Selected factors and their assigned levels for optimization study [11]

Symbol	Factors	Unit	Levels			
			1	2	3	4
A	Cooling rate	°C/min	1	2	3	4
B	Soaking temperature	°C	-80	-115	-150	-185
C	Soaking time	Hours	06	12	18	24
D	Tempering temperature	°C	125	150	175	200
E	Tempering time	hours	1	2	3	4

Their research found that cryogenic soaking temperature was the most significant factor and the optimum soaking temperature being in the range of -185°C. The second important factor was tempering temperature, the best level being 150°C. Other factors did affect the results of cryogenic treatment but were not as significant as soaking temperature and tempering temperature.

K Amini et al [12], worked on a research specifically to find the optimum soaking time during cryogenic treatment for which most optimum results can be obtained. In their work, deep cryogenic treatment was performed on commercial 1.2080 tool steel bar. Post austenising the tool at 950°C, cryogenic treatment of the tool was performed at a cooling rate of 1°C/min until cryogenic temperature then holding the samples at that temperature for different soaking time, and then again bringing it back to room temperature with heating rate of 1°C/min. Samples were tempered after cryogenic treatment at 180°C with holding period of 1 hour. The samples were differentiated on the basis of holding time of 24, 36, 48, 72, 96 and 120 h, and were named as DCT24, DCT36, DCT48, DCT72, DCT96 and DCT120, respectively. Their study concluded that micro structure, hardness, carbide percentage are affected by varying the soaking duration. Upto 36 hours of soaking duration the carbide percentage increases and carbide particles show more uniform distribution as compared to other lower holding duration. Further, on increasing the soaking duration above 36 hours, hardness tends to decrease and also there is reduction in carbide percentage and uniformity of carbide distribution. Hence, 36 hours of soaking duration is considered as optimum which results in maximum improvements in properties of tool steel.

Seyed Ebrahim Vahdat et al. [13], worked on the effect of micro-structure parameters on the tensile toughness of tool steel post deep cryogenic treatment. Also, they performed cryogenic treatment by varying two different parameters, soaking period and tempering time. In the research work, ten sets of tool steel were deep cryogenically treated at -196°C, the corresponding tempering time was 2 hours, at -196°C for 24, 36 and 48 hours and were tempered at 200°C

for 1, 2 and 3 hours. The treatment cycle consisted of austenizing, water quenching, deep cryogenic treatment and tempering. The results concluded that high population density and high content of high content of secondary carbides were two important parameters of microstructure, affecting enhancement of tensile toughness property of tool steel. The increased soaking time leads to constant increase of content of secondary carbide, however population density of secondary carbides increased until 36 hours of soaking time and reduces after this period. Although, the maximum tensile toughness was obtained in combination of 48 hours soaking at -196°C , and 2 hour of tempering, most optimum combination for improved tensile toughness property was found to be 36 hours soaking at -196°C , and 1 hour of tempering.

Previous researches done focused on effect of cryogenic treatment on general grade of tool steel widely used and the effect of different parameters of cryogenic treatment.

B. Podgornika et al. [14], conducted the research work to investigate the effect of DCT on fracture toughness, wear resistance and load carrying capacity of cold work tool steel. Also, one of the objectives of the research work was to determine the effectiveness of DCT depending on the tool steel type and chemical composition. The research work concluded that the type and chemical composition of the tool steel considerably affect the way how deep cryogenic treatment changes mechanical, tribological and load-carrying capacity of the tool steel. The results were that in case of low carbon cold-work tool steel, DCT results in greatly improved fracture toughness while maintaining high hardness. On the other hand, for high C cold-work tool steel DCT has negative effect, while for high-speed steel, DCT has practically no effect on its properties.

III. EFFECT OF CRYOGENIC TREATMENT ON ALLOY STEEL

Most of the research done earlier was on focused on effect of cryogenic treatment on tool steels. After noticeable advantages of cryogenic treatment were observed in tool steel, many research works were carried out for various other grades of steels like alloy steel, plain carbon steel and stainless steel.

A.Prabhakaran et al. [15], conducted the research work to evaluate the effect of SCT as well as DCT on impact strength of case carburised En353 alloy steel. En353 is an alloy steel with main alloying elements as chromium and nickel. It is generally case hardened to achieve direct properties of wear resistance, toughness, fatigue strength etc. It is used for applications such as material for shafts, pinions and clutch plates. In the study, specimens of En353 steel were treated as conventional treatment (case carburized at 930°C temperature), shallow cryogenic treated (after carburizing) and deep cryogenic treated (after carburizing). After respective treatments on specimens, they were tested for impact strength by carrying out charpy impact test. The results of impact test indicated that the impact strength of the material improved by same amount in case of SCT as well as DCT when compared to conventional treatment. Hence, the study concluded that the cryogenic treatment results in enhancing impact strength of En353 and only SCT treatment is sufficient for the same.

A. Bensely et al. [16], carried out the study for evaluating the effect of SCT and DCT on wear resistance of case carburized EN 353 steel. In this study also, the specimens were treated as conventional treatment (case carburised), SCT and DCT. The wear behaviour of differently treated material was evaluated by pin on disc type wear test without lubrication. The tests were carried out at three different load conditions (60 N, 70 N and 80 N) and at seven different sliding velocity (ranging from 1.5 m/s to 5 m/s). The results of the tests are as shown in fig.4

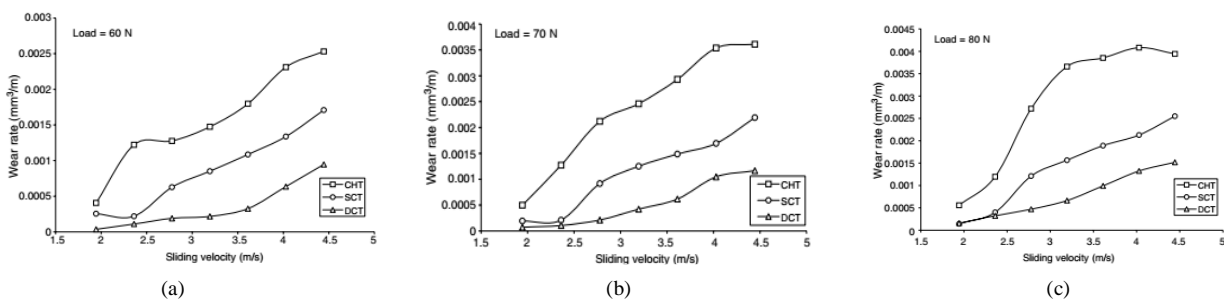


Fig. 4. Wear test results (a) Wear rate at 60 N load for three different treatments (b) Wear rate at 70 N load for three different treatments (c) Wear rate at 80 N load for three different treatments

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The results clearly indicate that SCT and DCT both results in improvement of wear resistance of En 353 steel when compared with conventional case carburizing treatment. The most effective treatment is DCT. Wear resistance improved by 85% for SCT and by 372% for DCT when compared with conventional treatment. Wear resistance by 152% for DCT when compared with SCT.

A. Bensely et al. [17], studied the influence of cryogenic treatment on tensile strength of the case carburized steel-815M17 (En353 steel). The tensile test of the case carburized, shallow cryogenic treated and deep cryogenic treated material was carried out to study the tensile behaviour. The conventional treatment was done by carburizing, air-cooling, quench-hardening in oil and tempering. Conventionally treated material without tempering were shallow cryogenic treated by placing directly in mechanical freezer at temperature 193 K and soaked for 5 hours. DCT was also carried out by after conventional treated by slow cooling the specimen at 1.24K/min, till 77 K with holding time of 24 hours. The results of the study concluded that there is reduction in tensile strength by 1.5% for SCT and 9.34% for DCT as compared to conventional treatment. But, as other properties like wear resistance and impact strength of cryogenic treated specimen enhances by considerably greater amount, slight decrease in tensile strength can be allowed. A. Bensely et al. [18], carried out a study to evaluate the effect of SCT and DCT on distribution of residual stresses in case carburised En 353 steel. Conventional treatment, SCT and DCT were carried out with and without tempering. For conventional treatment, six samples were subjected to liquid carburizing at 1183 K until the blank specimen reached a case depth of 1.2 mm. Then six samples were air-cooled, followed by hardening at 1093 K for 30 min. All the six specimens were then quenched from 1093 K in oil at 313 K. After this, 1 sample was separated as untempered, another one was tempered at 423 K for 1.5 h. Meanwhile, remaining four samples which were already quench hardened were subjected to SCT and DCT with and without tempering respectively. SCT was carried out in mechanical freezer at temperature 193 K and soaked for 5 hours. DCT was also carried out by after conventional treated by slow cooling the specimen at 1.24K/min, till 77 K with holding time of 24 hours. The tempered specimens of SCT and DCT were treated at 423 K for 1.5 h. Residual stress distribution was evaluated for each sample. The results showed that untempered conventional treated specimen had surface residual stresses of -125 Mpa. Whereas untempered SCT and DCT had surface residual stresses of -115 MPa and -235 MPa respectively. On the other hand, tempered and conventionally treated specimen had surface residual stresses of -150 MPa and tempered SCT as well as DCT had surface residual stresses of -80 MPa. Hence, it was concluded that cryogenic treatment with tempering can result into reduction in surface residual stresses by significant amount. The reason for such behaviour could be increased precipitation of fine carbides in cryogenically treated and tempered specimens.

A. J. Vimal et al. [19], studied the effect of cryogenic treatment being carried out at different stages of heat treatment on En 31 material. In the experiments conducted, the specimens of En31 were divided into four groups, A, B, C and D. Group A specimens were conventionally hardened by austenizing at 1093 K for 60 minutes, then oil quenching it. Quenching was followed by tempering at 423 K for 30 minutes. Group B specimens were immediately cryogenic treated at 90 K with soaking period of 24 hours after hardening and were tempered after cryogenic treatment. Group C samples were hardened, tempered and then cryogenic treated. Group D samples were hardened, tempered cryogenic treated and then again tempered. The wear behaviour of each group were tested by pin on disc type wear set up at different loads 20 N, 30 N and 50 N and different sliding velocity of 0.5 m/s, 1 m/s and 1.5 m/s. Also, hardness and microstructural analysis of different specimens were carried out to evaluate the mechanism behind varying wear resistance of differently treated material. Wear test results concluded that group B samples had the highest wear resistance. Hence, the optimum process of cryogenic treatment should be to subcool the material at cryogenic temperatures immediately after conventional hardening and tempering to be done post cryogenic treatment. The microstructure examination shows that the wear resistance and hardness of the cryogenic treated material increases subsequently due to complete transformation of austenite to martensite and precipitation of higher amounts of fine carbides of the size less than 0.5 microns during cryogenic treatment followed by tempering.

D. Senthil Kumar and I Rajendran, [20], studied the influence of SCT and DCT on wear behaviour of En 19 steel. In the study, the samples were treated conventionally quench hardening in oil at 875°C for 1 h. Other set of samples were shallow cryogenic treated in freezers at -80°C for 5 hours after conventional quench hardening. The another set was deep cryogenic treated after conventional quench hardening. The DCT was done -196°C with soaking time of 24 hours, ramp down rate of 1.26 K/min and ramp up rate of 0.64 K/min. All differently treated samples were tempered at 200°C

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for 60 minutes. After the respective treatment, hardness test, wear test and microstructure analysis were carried out. The wear test was carried out at lower load values of 10N, 20N and 30N as well as on higher load values of 60N, 70N and 80N. The test results showed improvement of wear resistance by 118.38% for SCT samples and 214.94% for DCT samples when compared to conventionally treated samples. In addition, the increase in wear resistance of DCT samples is 44.39% with respect to SCT samples. Microstructural analysis concluded that cryogenic treatment promotes transformation of retained austenite to martensite, thereby improving wear resistance.

Ibrahim Gunes et al. [21], studied the effect of different holding time in DCT on wear behaviour of AISI 52100 (EN 31). In the study, the samples were conventionally treated by austenizing at 850°C for 15 minutes followed by oil quenching and then tempering at 180°C for 2 hours. Another set of specimens were also conventionally hardened and tempered and then were subjected to DCT at -145°C with different holding time of 12h, 24h, 36h, 48h and 60h. The cryogenic treated materials were then subjected to tempering at 200°C for 2 hours. Hardness, wear rate and microstructure of different specimens were evaluated. The wear test was carried out by ball and disc method at 10 N and 20 N, with sliding velocity of 0.15 m/s and sliding distance of 600 m. The results of the wear test concluded that optimum holding time was found to be 36 hours, which showed lowest wear rate as compared with other specimens. The highest wear rate was found to be in conventionally treated specimen. The hardness of the material went on increasing with increase in hold time. The microscopic analysis confirmed that the DCT created homogeneous carbide distribution with a more uniform particle size and some newly formed small-sized carbides, also varying holding time effects the changes in microstructure.

M. Arockia Jaswin, D. Mohan Lal, [22] subjected EN 52 and 21-4N valve steel to cryogenic heat treatment and compared corrosion and thermal behaviour of deep cryogenic treated and conventionally heated materials. The conventional heat treatment was carried by austenitizing 1248 K for one hour, followed by oil quenching and tempering at 923 K temperature for one hour. DCT was carried out by slowly cooling the specimens from room temperature to 85 K at 1 K/min, soaking at 85 K for 24 hours, and finally heating it back to room temperature at 0.6 K/min. The corrosion test was performed by electrochemical method. The results of corrosion test concluded that the corrosion rate of EN 52 improved by 8.44 % when cryogenic treated, whereas 21-4N valve steel showed reduction in corrosion rate when cryogenic treated. Thermo-mechanical analysis was carried out to study the dimensional stability of the material. For both materials, lower coefficient of thermal expansion was found which indicates that cryogenic treatment can result into better dimensional stability. The study also concluded that dimensional stability can be attributed to the precipitation of alloy carbides and grain coarsening.

IV. EFFECT OF CRYOGENIC TREATMENT ON PLAIN CARBON STEEL

Plain carbon steel provides a good balance between strength and ductility, and it is common in many types of steel parts. Also, they are easily machinable as compared to alloy steel. Most commonly used heat treatment process for enhancing properties of medium carbon steel are quenching and tempering, carburizing. Various research is also been done to evaluate the effect of cryogenic treatment on plain carbon steel.

Mandeep Singh, Harpreet Singh, [23], carried out the study to evaluate the effect of DCT on wear behaviour of mild steel. In the study, the raw material specimens were conventionally treated by heating at 815°C, then water quenching it. Tempering at 150 °C for 1 hour was done after conventional hardening process. Other set of raw material which were conventionally hardened but not tempered were cryogenic treated by cooling it till -193 °C with a soaking time of 28 hours. Tempering was done after cryogenic treatment. Treated materials were tested for hardness, wear resistance and microstructure. There was significant amount of improvement found in hardness of cryogenic treated specimen. Pin on disc type wear test was carried out at three different loads of 30N, 40N and 50N. The wear test results showed the improvement of 21% in wear resistance of cryogenic treated specimen as compared to conventionally treated specimen. As per the microscopic examination, the microstructure of DCT specimens consisted of martensite and bainite which might be the reason for improved wear resistance. Harpreet Singh et al. [24], also evaluated the effect of DCT on corrosion resistance and mechanical properties of mild steel which underwent same conventional treatment and DCT. The results of the study concluded significant improvement in tensile strength and corrosion resistance of deep cryogenic treated specimens as compared to conventional treated specimens.

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T. Slatter et al. [25], studied the effect of cryogenic treatment on impact wear of low carbon steel (mild steel). In the study, the cryogenic treatment was carried out at -180°C with the holding period of 16 hours. Tempering was done after DCT to relieve thermal residual stresses. Tempering was done at a temperature of 170°C for period of 2 hours. The cryogenic treated and untreated specimens were subjected to repetitive percussion impact normal to their surface at 10 Hz (impacts per second) in a ball-on-flat configuration. The results of the test suggested there was positive impact of cryogenic treatment on impact wear resistance of low carbon steel.

Lakhani Mansi M and Niyati Raut [26], carried out the study to evaluate influence of cryogenic treatment on mechanical properties of EN 8 steel which is a medium carbon steel. In the study, test specimens were treated with conventional hardening which was done at 850°C and oil quenching and was followed by tempering done at 350°C for 2 hours. Other set of specimens were subjected to cryogenic treatment after hardening. Cryogenic treatment was carried out at -193°C with ramp down and ramp up rate of $0.5^{\circ}\text{C}/\text{min}$ and soaking period of 24 hours. Double tempering at 150°C for 1 hour was done after cryogenic treatment. The treated specimens underwent hardness test, tensile test, impact test and microstructure examination. The results of the test suggested that there was significant amount of improvement in hardness and impact strength of the material which was cryogenic treated. There was no change in tensile strength of material after cryogenic treatment. The microstructure of the cryogenic treated specimen revealed decreased amount of retained austenite and formation of small carbides when compared to microstructure of conventionally treated specimen

V. EFFECT OF CRYOGENIC TREATMENT ON STAINLESS STEEL

G. Prieto et al. [27], carried out the study to evaluate the effect of DCT and SCT on mechanical properties and microstructure of AISI 420 stainless steel. In the study, the conventional treatment was done by austenizing till 830°C and oil quenching. Tempering was done 410°C and furnace cooling. Different cryogenic treatments were performed after conventional hardening process as listed in table 2

Table 2: Different treatments performed on test specimens [27]

Identification	Description
CHT	Conventionally heat treated
DCT-1F	Cryogenic treated at -196°C for 1 h. Direct Liquid Nitrogen (LN) immersion
DCT-2F	Cryogenic treated at -196°C for 2 h. Direct Liquid Nitrogen (LN) immersion
DCT-1C	Cryogenic treated at -196°C for 1 h. $0.45^{\circ}\text{C}/\text{s}$ cooling rate
DCT-2C	Cryogenic treated at -196°C for 2 h. $0.45^{\circ}\text{C}/\text{s}$ cooling rate
SCT-1	Shallow cryogenic treated at -40°C for 2 h. $0.45^{\circ}\text{C}/\text{s}$ cooling rate
SCT-2	Shallow cryogenic treated at -80°C for 2 h. $0.45^{\circ}\text{C}/\text{s}$ cooling rate

Treated specimens were tested for hardness (Vickers), impact toughness (Charpy test) and microstructure analysis. The results of the tests concluded that DCT with 2 h soaking was enough to achieve 5% improvement in hardness and 10% improvement in impact toughness as compared to CHT. Also, stainless steel can sustain faster cooling rate but should not be directly immersed in LN and uniform ramp up and ramp down should be maintained. Cryogenic treatment leads to formation of higher amount of smaller secondary carbides with a more uniform distribution.

P. Baldissera et al. [28] [29], evaluated the effect of DCT on hardness, tensile strength, fatigue strength and corrosion resistance of AISI 302 stainless steel. In the study, different parameters of DCT were considered and optimum parameters were evaluated by full factorial design of experiments. Two different DCT temperatures of 143 K and 88 K and DCT soaking time of 9 hours and 24 hours were considered for treatment. The result of the study suggests that there is no significant improvement in tensile strength, hardness and corrosion resistance of the non-treated material. On the other hand, DCT had significant effect on improvement in fatigue limit and fatigue life. It was also concluded that soaking time of 9 hours was enough and longer soaking time was not required.

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J.D.Darwin et al. [30], optimized the parameters of cryogenic treatment to maximize the wear resistance of 18% Cr martensitic stainless steel by taguchi method. In the study two levels of 5 different parameters were considered as shown in table 3

Table 3: Different parameters and their level considered for optimization study [30]

Factor	Level	
	1	2
Cooling rate	1°C/min	3.5°C/min
Soaking temperature	-80 °C	-184 °C
Soaking period	6 h	24 h
Tempering temperature	150 °C	200 °C
Tempering time	1 h	4 h

The results of the wear test for specimens treated at different parameters concludes that soaking temperature is the most significant factor which improved wear resistance of the material by 72%. The optimum soaking temperature is found to be -184 °C. Second important parameter is soaking period which improves wear resistance by 24% and optimum soaking period is 36 h. Optimum cooling rate is found to be 1°C/min and contributes to 10% of improvement in wear resistance. Tempering temperature shows only 2% improvement and tempering period have no significant improvement in wear resistance of material.

VI. CONCLUSION

Following conclusion can be suggested regarding the effect of cryogenic treatment on different grades of steel from the in depth review of literature done in this paper:

1. Cryogenic treatment is not the substitute but the supplement to conventional heat treatment.
2. For cryogenic treatment to be more effective, tempering should always be done after cryogenic treatment.
3. Cryogenic treatment of tool steel results in significant increase in wear resistance of tool steel and tool life as compared to conventionally treatment of tool steel for different applications like turning, drilling and milling.
4. Cryogenic treated tool steel gives superior performance as compared to TiN coated tools.
5. Cryogenic treatment is not effective when done on coated tool material
6. Most important parameter that affects the results of cryogenic treatment on tool steel is soaking temperature and its optimum value is around -175 °C to -196 °C.
7. Cryogenic treatment also results in improvement of tensile toughness and fracture toughness of tool steel.
8. Cryogenic treated case carburized or hardened tempered alloy steel shows significant amount of improvement in properties like impact strength, wear resistance, dimensional stability, corrosion resistance with slight reduction in tensile strength.
9. Impact strength of Shallow cryogenic treated and deep cryogenic treated alloy steel is found to be same, where as DCT gives better results for other properties as compared to SCT.
10. Soaking period of 36 hours is found to be optimum for both tool steel and alloy steel
11. Cryogenic treatment of mild steel results in improvement of hardness, tensile strength, wear resistance and corrosion resistance as compared to conventionally hardened and tempered mild steel.
12. Cryogenic treatment also results in improvement in hardness and impact strength of medium carbon steel.
13. In case of stainless steel, cryogenic treatment found to be effective even with lower soaking period of 2 hours and 9 hours.
14. Cryogenic treatment tends to improve fatigue strength and wear resistance of stainless steel without compromising property of tensile strength and corrosion resistance.

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15. The most important mechanism responsible to enhance properties of different grades of steel through cryogenic treatment is found to be conversion of retained austenite to martensite and formation of precipitated secondary carbides.

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