Rev. Adv. Mater. Sci. 51 (2017) 149-159

A REVIEW ON EFFECTS OF CRYOGENIC TREATMENT OF AISI 'D' SERIES COLD WORKING TOOL STEELS

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Received: May 16, 2017

Abstract. The influence of incorporating different cryogenic phases in the heat treatment sequence of D series cold working tool steels is reviewed. The micro structural changes taken place for different grades of cold working steels under this series, by incorporating a cryogenic treatment process within the conventional heat treatment cycle is focused for this review analysis. Also, the changes in mechanical as well as tribological properties of these steels due to this additional treatment are discussed with emphasis on the factors contributing to the enhancement of these properties. AISI D series represents tool steels with high carbon and high chromium contents which exhibit good post treatment hardness and are having good machinability in the pre treated conditions. Hence, they are widely used for making press tools, plastic moulds, knifes, blades etc which need good wear characteristics. D2, D3, D5, D6, and D7 are the grades of tool steel selected for this review. The improvements obtained by the deep as well as shallow sub zero treatments conducted in various sequences of operations are noted. Comparisons within the material and within the series are reviewed for different cases. The advantages and disadvantages of having cryogenic treatment as a secondary heat treatment for D series tool steels are highlighted.

1. INTRODUCTION

Cryogenic treatment process or sub zero treatment has become a part of heat treatment cycle to improve the mechanical and tribological properties of steel. The word cryogenics is originated from Greek word kryo means frost or frozen. The study related to this low temperature process or treatment is covered under the scope of cryogenics. In this process, work piece is treated in the presence of liquid nitrogen below atmospheric temperature and the micro-structural changes due to this treatment reduce the percentage of austenite retained in the steel by converting it into martensite and thus improve both mechanical as well as tribological characteristics.

The main objective of this review is to go through various studies carried out in the field of cryogenic treatment on cold working tool steels, with focus on process adopted and influential parameters and their effects on the microstructure and phase transformations. The changes occurred in the mechanical and tribological behavior due to this process and the reasons behind such conditions are also reviewed. The summary provides an insight into the effects of cryogenic treatment of cold working tool steels as a secondary treatment if incorporated with the conventional hardening process of the cold working tool steels. The work represents the first step of a research project carried out in the heat treatment for tool steel used in heavy duty blanking and forming tools used in the switch gear industry to reduce the wear and to increase the overall tool life.

1.1. Cold working tool steels

Tooling is an important aspect in mass production and an increased tool life will give better productiv-

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ity thus enhancing efficiency and economy at the same time. Cold working tool steel is widely used to manufacture press tools, different types of moulds, dies etc. If the hardness is more, the material will become brittle and at the same time, too less hardness will lead to more wear and deformation. An ideal condition of hardness and toughness is required for a longer tool life. Different kinds of tool steels are developed with proper alloying to suit the demanding requirements of the industry. To select the best option we should be aware of the type of wear mechanisms that can occur in the tooling operation. Abrasive and adhesive wear are common which are based on the surface hardness of the tooling material and the working component material. The review is specifically focused on the various studies conducted on cold working tool steel with higher percentage of carbon and chromium, which are widely used for press tool manufacturing for cutting and non cutting operations.

The cold working steels with high carbon content and suitable proportion of other alloying elements can be quenched without much distortion and are comparatively inexpensive and hence generally used for press tools where wear and toughness are equally important. These types of tool steels are classified under the category of D series with carbon percentage of 1.5% to 2.35% with a chromium percentage of up to 12%. If molybdenum is not present as in case of D3 series, this can be oil quenched and when molybdenum is present as an alloying element, air quenching is carried out.

The physical characteristics exhibited by cold working tool steels include low distortion while quenching, high hardness on proper treatment, easy to machine in annealed condition. They got better wear resistance and strength. They are classified based on the quenching medium and alloying composition. 'W' series are water quenching and 'O' series are oil hardening. 'A' series is for medium carbon alloy with air hardening and 'D' series is high carbon high chromium alloy steel and can be hardened in air and oil medium depending upon other alloying elements.

2. HEAT TREATMENT

Heat treatment techniques are being carried out on metal products to improve their properties and practiced from ancient time and is being performed till today at various degrees and levels. In most of the cases, the metal will be heated to a critical temperature and then cooled to alter the microstructure for better properties [4].

In general, tool steels are supplied in annealed condition and will be soft in nature so that the same can be machined easily and also it bears a microstructure that can become hard upon heat treatment.. Tool steels will exhibit its quality upon proper heat treatment and will differ depending upon the composition of alloying elements. The conventional heat treatment process includes hardening or austenizing, quenching and then tempering [5].

Upon analysis of the micro structure of conventionally heat treated tool steel, we can find a reasonable amount of retained austenite and if we can convert these retained austenites to martensite while performing the tempering process, the overall tool life can be improved. The significance of cryogenic treatment as an intermediate process is playing its role for converting the retained austenite to martensite and thus giving a better homogeneous structure. Cryo- treatment is developed as supplementary treatment for tool steels along with the standard heat treatment process to increase the wear resistance and dimensional stability thereby improving the tool life. Various studies in this direction had revealed that, tribological and mechanical properties of different grades of tool steels can be improved by incorporating a sub zero treatment cycle in between the conventional heat treatment process.

2.1. Hardening

Heat treatment process begins with hardening also called as austenizing. Upon heating steel to hardening temperature, the ferrite phase will change to austenite. The austenite by large is coarse grained irregular structure and martensite is fine grained hardened structure. By hardening, the austenite structure transforms to martensite. This transformation begins at a temperature called as M_S or martensite start temperature.[7]. The structure of these phases and the orientation of carbon and iron atoms are shown in Fig. 1. For cold working series, this change in phase is isothermal and will cease upon reaching M_F or martensite finish temperature. After hardening of steel, certain amount of austenite will be present in the matrix which is termed as retained austenite. The percentage of carbon in the steel influences the martensite start and finish temperatures and also the final hardness of the steel. The start and finish temperature will vary based on the grain size also [8]. The optimum austenization temperature varies from metal to metal and will be different for the different grades of the D series cold working tool steels.

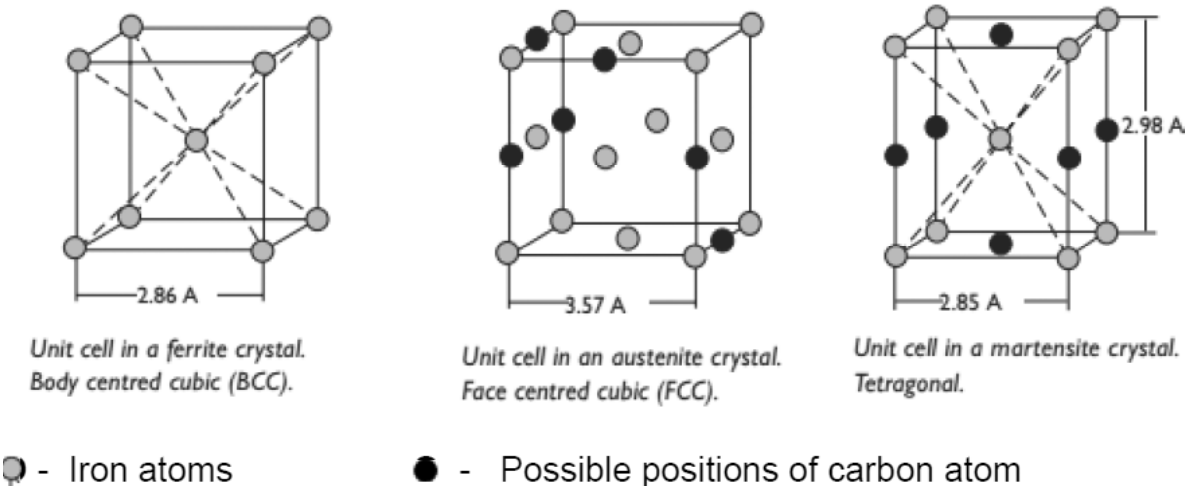


Fig. 1. Iron carbon orientation, reprinted with permission from *Technical catalogue on Heat Treatment of Tool steels* (Uddelhom, Assab, 2012).

Fig.1 shows the position of iron and carbon atoms in ferrite, austenite and martensite phases. It is clear that, the carbon atom changes its position in atomic lattices and generates a different crystal in different phases. The carbon and other elements in the alloy are more soluble in austenite phases and different carbides are formed in the matrix which will give the hardness for the steel without coarse grains. On suddenly quenching the steel during the treatment process, the carbon atoms will not get enough time to acquire its position to gain back the ferrite structure, but will get fixed in the positions where it may not have sufficient space which leads to higher micro-stresses and this will contribute to the higher hardness. This hardened phase formed is termed as martensite. While hardening, steel the matrix will not entirely get converted into martensite but there always remains some amount of austenite. These remaining austenite in the matrix is called as retained austenite [4,8]. The structure of quenched steel will have martensite, retained austenite and carbides of alloys and are the factors affecting the hardness of the steel.

2.2. Tempering

More alloying elements and their percentage, higher temperature for hardening, long soaking hours and slower quenching can result in increased retained austenite content. The inherent stresses within the structure can easily create cracks and the same can be prevented by heating this again to a lower temperature which can reduce the stresses. By this reheating, a portion of retained austenite will also get converted and this process of reheating after initial hardening is known as tempering. Even after multiple tempering also there remains retained austenite.[5,9]. But tempering has to be followed by hardening and depending upon the type of steel it can be two or three steps.

The properties of the material are improved during tempering but their austenitic crystal structure remains the same after the process which is soft in nature. Most of the cold working tool steels are having secondary hardening properties and hence optimizing tempering process is very important to achieve the desired results. After applying the cryogenic treatment austenite is permanently transformed into the martensite structure which represents permanent change in micro structure. This martensite structure definitely increases wear resistance capacity, toughness and thus mechanical property is in increasing order. Basically, all these improved characteristics are result of formation or transformation of martensite from austenite structure which is soft phase of iron and carbon atom [10]. This un-transformed austenite is brittle and not durable which allows the metal to break under minimum application of loads. The presence of retained austenite which is soft in nature can reduce the tool life and during working it can get converted to martensite but that will be brittle in nature and differs from the tempered one. Thus tempering single or multiple plays a key role in the final product characteristics and its overall life.

3. CRYOGENIC TREATMENT

Cryogenic treatment is carried out as a process within the heat treatment cycle by cooling below atmospheric temperatures with liquid nitrogen. It is classified as shallow cryogenic treatment and deep

Table 1. Chemical composition of D2.

ELEMENT (%)	C	Si	Mn	Cr	Mo	V
D2	1.5	0.3	0.4	12.0	0.8	0.8

cryogenic treatment. Though initiated in the beginning of 20th century, real importance of the cryo-treatments has been noticed only during the last years of the century. The basic cryogenic treatment process is cooling down slowly to sub zero temperature and holding there for certain duration, freezing time and then gradually bring back to room temperature [12]. This is done to achieve enhancement in mechanical properties and tribological properties especially to optimize hardness and toughness. Currently, cryogenic processing is widely used in aerospace industry and various other manufacturing industries. A wide range of research and analyze are carried out by using cryogenic treatment in the field of tooling industry to improve the wear performances of the steel [14]. Though a clear mechanism for this improvement being not defined, various hypothesis with changes in micro-structural behavior are discussed in literature and analysis of experimental studies conducted in this direction.

Before cryogenic treatment, carbon in austenite structure having poor bonding and bond strength while after the process the carbon atoms are very closer to iron atoms and thus they give strong bonding characteristics to the microstructure. In majority of the studies, two mechanisms are identified as the reason for the increased mechanical properties when it undergoes cryogenic treatment. One is conversion of retained austenite left during hardening to martensite and the other one is the precipitation of carbides and its nucleation within the lattice [8]. Martensite which is hard in nature because of the orientation of carbon atoms in the lattice offer better resistance to plastic deformation than austenite structure. Additionally, the precipitation of nano-carbides during tempering will also lead to better mechanical properties.

3.1. Effect of cryo treatment on D2 tool steel

D2 steel from AISI D series (the composition is given in Table 1) is hardened by the process of vacuum hardening and then tempered in the conventional method. But it is recommendable to add an additional operation of sub zero treatment in between the hardening and tempering cycle which could improve the final properties of the product and assure reduction in dimensional distortion. The tempering can be of single or multiple steps in a temperature range from 520 °C to 540 °C. The deep treatment at a temperature of -150 °C gives better dimensional stability and the duration of cycle or freezing time is not very influential [18].

While hardening D2 tool steel, increase in autenizing temperature increases the hardness to a certain extent and then drops down due to the presence of retained austenite formed at elevated temperatures. With cryogenic treatment, peak hardness becomes more and can be obtained at a higher austenizing temperature [19]. After cryogenic treatment, the toughness of the steel shows improvement which is due to the micro-structural changes taking place within the martensite itself and this improvement in toughness will be more for samples with lower austenizing temperatures. By cooling, martensite forms continually below the normal transition temperature and holding further in the same temperature range, promotes the precipitation of fine carbides in large amount in tempering.

Fracture toughness is an equally important property when it comes to the tool or die steel. Wear resistance depends upon hardness as well as toughness and optimizing these two parameters can give economical tool life. The most common failure mechanisms in tools which include cracking, chipping, galling etc can be reduced by controlling the fracture toughness of the steel used for making punches and dies. A study conducted on the fracture toughness of D2 tool steel [16] revealed the amount of dissolved carbon and other alloying elements play a vital role in achieving proper toughness. In the case of D2 fracture toughness can be improved by refining the carbides present in the matrix by heat treatment conditions and controlling the elements for alloying.

The increase in hardness by deep cryogenic treatment is due to the crystallographic and micro structural changes and fine distribution of micro carbides [20]. This increases the hardness and thus reduces the wear rate. Formation of fine nano carbides enhance the wear properties while coarsening of carbides decreases the wear rate. Even for the same hardness, the wear rate can vary based on the presence of fine carbides and its distribution

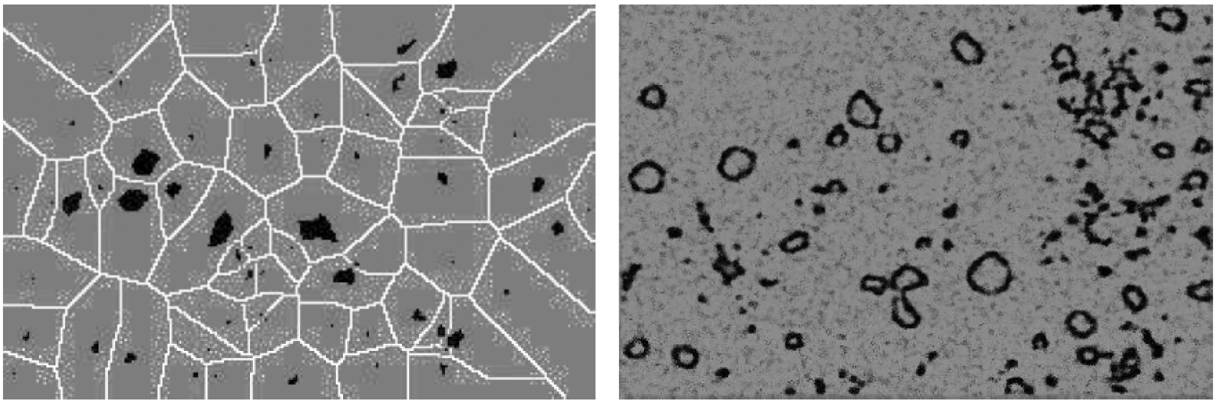


Fig. 2. Structure of D2 with large and small secondary carbide.

pattern. Cryogenic treatments help to modify the precipitation of metallic carbides, obtaining a finer and even distribution [21]. Farina et al. (2011) in their study, indicated the presence of homogeneous distribution of nano carbides after the cryogenic treatment [22]. The influence of sub zero treatments on microstructure and hardness of D2 and formation of large and small secondary carbides are explained in the study conducted by D. Das et al. [23]. Fig. 2 shows the image with voronoi cells for expected microstructure with small and large secondary carbide precipitation with martensite.

Another study of heat treated samples of AISI D2 steel in different conditions with conventional and cryogenic treatment were conducted for the influence of such treatments on the wear behavior of D2 steel [24]. The factors analyzed using SEM and image analysis are conversion and conditioning of martensite, precipitation and volumetric fraction of eta(η') carbides. The sequence of solidification of an AISI D2 tool steel begins with the austenite formation followed by the eutectic reaction, where primary carbides are the carbides precipitated directly from the liquid and eutectic carbides are the carbides precipitated from a eutectic reaction. This work focus more on micro structural changes and carbide precipitation during tempering done after cryogenic treatment and the precipitation of fine uniformly distributed carbides during this tempering cycle which is contributing to the enhanced performance of D2 [24].

K Singh et al. studied the influence of multiple tempering and abrasive wear behavior of D2 [25] and concluded that the wear resistance increases with finer morphology of carbides and martenstic formation. Another study in this direction [26] has been done regarding the changes in micro structure, impact toughness, abrasive wear and hardness of D2 with sub zero treatment prefers deep cryogenic treatment over shallow low temperature treatment. It was concluded on the basis of measurements obtained from optical micrographs for the population density of carbides. These changes are due to the sub structural changes and conditioning of martensite during sub zero treatments which results in precipitation of finer carbides in the matrix.

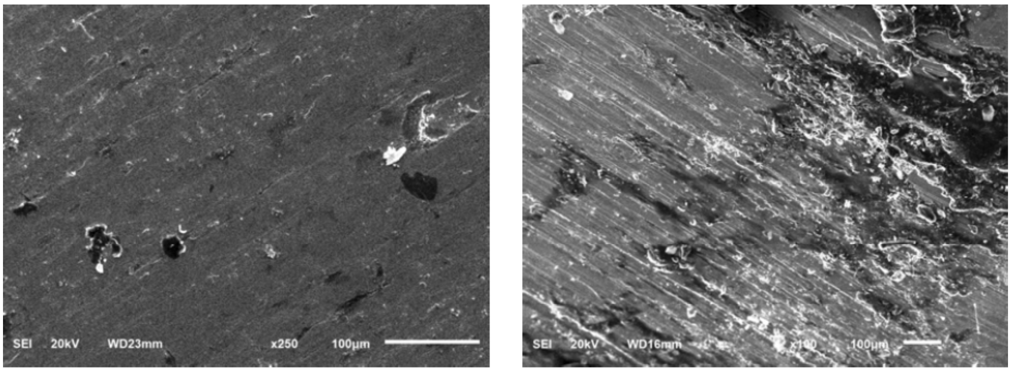
3.2. Effect of cryogenic treatment on D3 tool steel

The mechanical properties of cold working tool steel were studied [23] by analyzing the behavior of D3 and D2 tool steel with cryogenic treatment before and after tempering and it was concluded that D3 is showing better results with very less retained austenite while D2 exhibited an improvement when the sequence of hardening, quenching, cryogenic treatment and finally tempering was followed. In this pattern, the retained austenite is almost absent for D3 while D2 still shows a certain percentage of retained austenite. The chemical composition of D3 is given in the following Table 2.

In this study conducted on AISI D3 tool steel [26], results of deep cryogenic treatment on the various properties are examined and the correlation between wear rate and surface hardness is

Table 2. Chemical composition of D3.

ELEMENT (%)	C	Si	Mn	Cr	W	V	Ni
D3	2.35	0.4	0.6	12.0	1.0	1.0	0.3



a. With single tempering b. With multiple tempering

Fig 3. SEM photograph of D3 steel with (a) single and (b) multiple tempering.

analyzed. Due to elimination of retained austenite during the deep cryo treatment, significant hardness s realized. Experiments are conducted on three different samples, one raw, one with conventional treatment and final one with deep cryogenic treatment. Results revealed that the micro hardness of the cryo treated sample is highest while the raw is lowest and also lower frictional coefficient for cryogenically treated sample. Addition of deep cryogenic treatment process in the thermal cycle shows significant improvement of tribological properties when compared to the one treated in conventional cycle. In wear tests, this sample gives reduction in friction and wear under different loading conditions. Results confirm that the deep cryogenic treatment is an effective way to enhance the tribological and mechanical properties of D3 tool steel.

In the work conducted on multiple tempering of D3 tool steel [27], cryogenically treated D-3 steel shows reduction in hardness on multiple tempering and it keeps on reducing on further tempering. The SEM photographs of D3 steel treated with single tempering and with multiple tempering are shown in Figs. 3a and 3b, respectively. The wear rate was lowest in single tempered D3 steel while subsequent tempering deteriorates the wear resistance of D3 tool steel. Again it is observed that the wear rate is a strong function of carbides and its distribution. Fine carbides attributes wear resistance while coarseness lowers the wear resistance.

The worn out shearing punches normally exhibits flank wear and surface wear where mechanisms like abrasive wear, fretting, cavitation, adhesive and diffusion wear were observed. The retained austenite content has drastically reduced in cryogenically treated punches and the study conducted by Y Arslun et al. [28] on soaking time, concluded that the longer duration leads to more fine carbides distribution and better wear resistance. The mechanical response and overall performance improved with cryogenic treatment thus prolongs the tool life. The wear resistance is more when the tempering is performed after cryogenic treatment and it varies depending upon the loading pattern [29].

The investigation by Naravade et al. is focused on the effect of cryogenic treatment on austenitic ductile iron D3 tool steel for increase in hardness and enhancement in the wear resistance of the material. The cryogenically treated samples wear out slowly when compared to untreated samples confirming the enhancement in wear resistance there by increasing the tool life. The increase in hardness makes the material better with regard to mechanical properties. The investigation also confirms cryotreatment as an efficient onetime process to reduce wear in the austenitic ductile iron type D3 tool steel. The cryogenic treatment leads to an appreciable increase in wear resistance of the material. It is found that the percentage change in wear is lower for higher speeds thus leading to dependence of wear resistance on speed. The lumps of wear particles formed suggest the initial adhesive wear. Furthermore, the wear debris causes three body abrasive wear. It was concluded that the coefficient of friction decreases when austenitic ductile iron type D3 tool Steel is treated cryogenically [30].

3.3. Effect of cryogenic treatment on D5 tool steel

The friction and wear behaviour of D5 tool steel had been done by S.S Dixit et al. with different types of heat treatment processes including multiple tempering and post and pre cryogenic treatment to optimize the sequence of operation [31]. The alloying composition of D5 tool steel is shown below in Table 3. Wear test report reflects that the coefficient of friction of D5 tool steel increases due to

Table 3. Chemical composition of D5.

ELEMENT (%)	C	Si	Mn	Cr	Mo	V	Co	Ni
D5	1.50	0.4	0.6	12.5	1.20	1.0	3.5	0.3

Table 4. Chemical composition of D6.

ELEMENT (%)	C	Si	Mn	Cr	W
D6	2.1	0.3	0.6	12.0	1.1

multiple tempering before and after the cryogenic treatment. The highest hardness is observed in the specimen with single post cryogenic tempering. Hence, the lowest wear rate is shown by this specimen and is due to the additional amount of fine carbides formed during cryogenic treatment.

The wear rate depends upon normal load and sliding velocity. The wear rate or volume in general increases with sliding velocity and load, but in D5 it increases with load but fluctuates with sliding velocity. This is due to the microstructure formed from the different heat treatment conditions. It can be stated that the reduction of retained austenite percentage and alterations in the size and distribution of carbides are the main factors attributing for the enhancement of wear performance. This is obtained from the process sequence of hardening, cryogenic treatment followed by tempering and the results are better than by any other treatments in various other sequences [32].

3.4. Effect of cryogenic treatment on D6 tool steel

In the study conducted by A. Akhbarizadeh et al. [33] on the cryogenic effect in the treatment of D6 tool steel, they concluded that the wear performance was improved after the treatment. They carried out their work in deep cryogenic condition as well as increasing the period of cryogenic soaking time. The percentage of retained austenite goes down and more homogenous carbides are formed by treating D6 at sub zero temperature. Their work also covered the effect of multiple tempering before and after cryogenic treatment on the wear behavior of D6 with wear and friction tests. Deep cryogenic treatment at -185 °C for 36 hours included along with the normal heat treatment process of hardening to 1020 °C and then tempering at 210 °C. The wear tests were conducted at two different load and speed combinations. On analysis of the results of properties and microstructure, it is clear that the hardness and wear resistance had improved [34]. Table 4 gives the chemical composition of D6.

Fig. 4 below shows the micro structure of D6 after cryogenic treatment. It is inferred that, after deep cryogenic treatment performed below -125 °C hardness and wear resistance are more as the retained austenite transformation to martensite is higher and better distribution of carbides in higher proportion and homogeneous manner [35]. Shallow treatment was done at higher temperature range up to -90 °C. By deep treatment the wear characteristics of the D6 tool steel gets improved showing lesser abrasive wear. Narvade et al. in their comparison study of different heat treatments on D6 tool steel had come to the conclusion that cryogenic treatment is a better as secondary treatment than multiple tempering for the conversion of retained austenite to martensite [36].

If the metal is cooled down gradually to the cryogenic temperature and soaked for a longer time, the structure of the lattice changes. This change occurred due to relieving of stresses whereby soft FCC structure transforms to harder BCC structure on reaching the room temperature. Along with this, precipitation of newly formed carbides makes the structure harder thus giving more wear resistance [38].

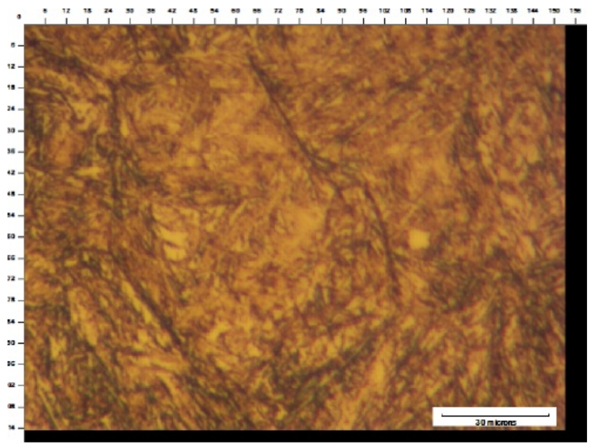


Fig. 4. Micro structure of D6 after cryogenic treatment.

Table 5. Chemical composition of D7.

ELEMENT (%)	C	Si	Mn	Cr	Mo	V
D7	2.4	0.4	0.6	12.5	1.2	4.20

3.5. Effect of cryogenic effect on D7 Tool steel

AISI D7 is an air hardening tool steel with high content of carbon and chromium, chemical composition as shown in Table 5. It displays exceptional resistance to wear because of the added carbon and vanadium. This produces vanadium carbides on treatment which is hard in nature. It is used in case where there is abrasive wear [38]. D7 is used for mold liners, blasting equipment liners, machine tool ways deep drawing and forming dies etc. The cryogenic study conducted on vanadis 4 which falls in between A7 and D7 grade also gives an improved tribological properties after the deep cryogenic treatment [39].

Though much research work is not carried out in case of D7 tool steel, we can presume that there will be considerable increase in the wear resistance after performing cryogenic treatment. It is already being understood that, the increase in wear resistance after cryogenic treatment varies from few percent to few hundred percentage for other cold working tool steel in the same series. The aspects behind the wear resistance improvements such as conversion of retained austenite and fine metallic carbide formations can be applicable for D7 also.

A concise table of reviewed papers summarizes their major findings and conclusion (Table 6).

4. CONCLUSIONS

The major valid findings that can be concluded from the above discussions are the formation of martensite from the retained austenite by cryogenic treatment and carbide formations. The lattice struc-

Table 6. A concise table of reviewed papers.

#	Author	Material	Treatment	Observations
1	H.G Naneesa et al.	D2	173K SCT	Better Dimensional stability is observed and Cycle time is not influential
2	K. Amini et al.	D2	Cryogenic	Hardness peaks due to more martensite and fine nano carbides precipitation. Improvement in toughness is observed
3	D Viale et al.	Tool steel	Cryogenic	Effect of carbon and alloying element in achieving fracture toughnesss is noticed during.
4	Farina P F et al.	D2	Cryo genic	No change for micrometric or primary carbide while uniform distribution found in nano or secondary carbides due to more martensite conversion from retained austenite.
5	D.Das et al.	D2	SCT and DCT	Formation of large and small secondary carbides and their uniform and homogemeous distribution
6	D.Das et al.	D2	Cold. SCT and DCT	Cracking of primary carbides and formation of micro structural voids causereduction in fracture toughness
7	Lio Chiu et al.	D2	Conventional HT and cryotreatment	The material loss observed during wear test is less after cryo treatments due to more uniform carbides present.
8	K.Singh et al.	D2	Multiple tempering	Abrasive wear enhancement due to higher hardness attributed to martenstic microstructure with morphology of carbides

9	N.W. Khun et al.	D3	DCT	Reduction of fiction and wear due to elimination of retained austenite
10	N.B. Dhokey &S. Nirbhavane	D3	Multiple tempering and cryo treatment	Wear rate deteriorates in subsequent tempering. It is a strong function of fine carbides and its distribution
11	Y. Arslan et al.	D3	DCT for cold shearing punches	Wear rate improves with more soaking time . 50% of the retained austenite in the untreated sample gets transformed to martensite. Thus cryo treatment an alternative to prolong the life.
12	Shaikh Ather & S. A. Sonawane	D3	Conventional HT and cryo treatment	Sliding wear test comparison showing improvement but also depends on loading patterns as load increases the wear rate also increases.
13	Swadesh Dixit	D5	DCT AND SCT	Wear study of specimen with different process sequence of heat treatment and DCT before tempering is suggested for better results.
14	S. Dixit et al.	D5	Wear Analysis by DOE/RSM	Wear rate increases with load but fluctuates with sliding velocity
15	A. Akhbarizadeh et al.	D6	SCT and DCT	Soaking time improves the conversion of retained austenite to martensite
16	A. Kaushal et al.	D6	77K DCT	Improved Wear resistance, Hardness and Toughness
17	A. Akhbarizadeh et al.	D6	DCT	Longer time gives better homogeneous structure and hence better tribilogical properties.
18	R.H.Naravade et al.	D6	Conventional and cryo treatment	Effect of inclusion of cryo treatment with conventional HT cycle and results were encouraging.
19	R.H.Naravade et al.	D6	DCT AND SCT	Wear rates are compared and found that increasing cryo temp and time improves the properties
20	K. Moore & D.N Collins	H13, D2 &D7	Cryo treatment	Improvement in hardness , independent of soaking time

ture of the martensite obtained from the cryogenic treatment is different from one obtained by conventional heat treatment. The matrix obtained with conventional heat treatment is composed of martensite, retained austenite and eutectic carbides and the sub zero treatment reduces retained austenite and refines the martensite. In case of D3 retained austenite reduction is more than D2 and D6. However, all the materials of this category of cold working tool steels exhibit a good reduction in retained austenite.

Another aspect is the precipitation of carbide particles depending upon the duration of the process and this time dependent formation of nano carbide particles are contributing to improve the mechanical properties of the cold working tool steels after cryogenic treatment. As the percentage of metals and carbon in the composition increases the hardness and wear resistance improves because of more fine carbide formation. Deep cryogenic treatment is the reason for the nucleation of the carbides and with this the fine carbide formation temperature is also coming down. As the tempering temperature is increased, the hardness decreases but the wear resistance and impact energy improved and are more prevailed in deep treated samples. The structure revealed that the post cryogenic tempering gives better results than tempering done before cryogenic treatment. It was found that, the best cycle that can be adopted for the sub zero treatment of cold working tool steel is hardening, quenching followed by cryogenic treatment and finally tempering. Depending upon the type of composition of metals in the tool steel, multiple tempering may be considered.

From this review, it can be concluded that the hardness of cryogenically treated sample is higher when tempered in low temperature than tempering in higher temperature. A significant improvement in wear resistance of cryogenically treated steels is observed in sliding abrasion tests when compared to tool steels that are conventionally heat treated, quenched and tempered. The reduction in temperature of the cryogenic treatment further to – 196 °C results in further enhancement in the wear resistance. In general, these studies attribute to the achievement of enhanced mechanical and tribological properties to the formation of martensite from the retained austenite and the small but hard carbide particles within the martensite matrix.

Cold working tool steels are widely used in the industry for tooling and molding and any study contributing to the enhancement of wear resistance and tool life will have a considerable impact. The wide nature of its application in different types of industries keep the area wide open for further studies specifying to the desired application or industry.

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