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Tribological studies on deep cryogenic treated aisi t42 high speed steel using response surface methodology

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Abstract: High – speed steels are the most widely used tool material in small and medium scale industries, owing to their excellent toughness and economic price over their competitors. But the wear resistance and hot hardness of high-speed steels are poor compared to tools made out of carbides. Recent investigations, on the effect of cryogenic treatment have proved to be an alternative option to enhance the hardness and wear resistance of high-speed tool materials. But so far only a limited number of investigations have been made into the effect of cryogenic treatment on different grades of high-speed steels. The present research reports the effect of deep cryogenic treatment on AISI T42 grade high – speed steel, with specific emphasis on mode and mechanism of wear. Wear behavior has been studied using pin-on-disc tribo-meter under dry condition. Response surface methodology was adopted in designing the experiments for two factors with five levels. Mathematical model has been developed incorporating the effect of sliding velocity and load on the wear behavior. Sliding velocity was found to be dominant factor than normal load. Morphology of worn surface and the wear debris was studied using SEM to identify the mode and mechanism of wear. Mild oxidative wear was the dominant mode of wear throughout the range of variables used in this study. Deep cryogenically treated specimens exhibited significant improvement in wear resistance than conventionally heat treated specimens, especially at higher sliding velocities. The wear rate of conventionally heat treated specimen was found to be 3.138 to 2.493 times higher than that of deep cryogenically treated specimens. There was an increase in hardness value form 66.8-67.2 HRC at the end of conventional heat treatment to 69.5-70.2 HRC at the end of deep cryogenic treatment.

Keywords: Cryogenic Treatment, Wear Rate, Response Surface Methodology, Mild Oxidative Wear, Morphology

1. Introduction

The demand for cutting tool material able to withstand high forces, high contact pressures, high temperatures and intense chemical transactions at the interface between tool and work piece is a dynamic phenomena and its effective management acts as a key to economy of production and industrial competitiveness [1]. Very often, the maximum material removal at optimum cutting conditions is the criterion practiced in metal cutting operations. As a result, the cutting tool material is always subjected close to their ultimate resistance against wear and chemical activities [2]. Though there is a wide range of high performance cutting tool materials such as carbides, cermets, ceramics and cubic boron nitride, which address the above demands, high-speed steel still remains a logical choice, as a tool material for many metal cutting operations, possibly because of its relatively high toughness, low price and possibility of economic manufacturing of tools with complex geometry. In certain applications such as deep drilling high speed steel is the only choice due to its excellent toughness.

Though high- speed steel was introduced a century ago with time it has undergone several modifications resulting in various grades suitable for variety of applications. The presence of allying elements and the domain of heat treatment confers the required qualities. Further, the use of secondary process such as hard abrasive coating enhances the wear resistance of these tools.

In the past two decades, there is an increasing amount of interest, in the use of cryogenic treatment, to enhance the wear properties of tool materials [3]. Specifically the earlier research works carried out on the effect of cryogenic treatment on high-speed steels, unambiguously confirm transformations in microstructure, improvement in hardness and wear resistance. And these changes take place across the entire volume of material, unlike the coating technique in which the wear property is enhanced only at the surface. Hence coated tools lose their wear resistance, once the coating wears out. But the advantages of cryogenically treated tools could be brought into full potential, after every regrinding. Therefore cryogenic treatment could spectacularly reduce consumption of tool materials.

When compared to heat treatment the cryogenic treatment is considered to be a recent development and it is still in its infancy, requiring rigorous experimentation and optimization before its establishment for commercial applications. The results of cryogenic treatment largely depend on rate of cooling, the lowest temperature used in the cycle and the soaking time [4, 5, 6]. Apart from this a low temperature tempering is applied at the end of cryogenic treatment to relieve the residual stresses and promote precipitation of fine carbides.

Until 1960s, researchers attempted to dip metallic components in liquid nitrogen which resulted in failure of components by cracking due to thermal shock. Later, the breakthrough in refrigeration cycles led to the development of cryogenic treatment systems with a feed back control on temperature, during cooling and warm up.

The effect of cryogenic treatment on cutting tool materials was first validated by Barron [5] in the year 1988 .He confirmed significant improvement in wear resistance of cryogenically treated AISI M2 specimens, compared to conventionally heat treated specimens, in sliding abrasion wear tests. He also verified that wear resistance still improved for components soaked at - 196˚C than at - 84˚C for a constant soaking time of 24 hours. He attributed improvement in wear resistance to both transformation of retained austenite and precipitation of fine carbide particles well distributed in the martensite matrix.

Presence of austenite, is inevitable in heat treated high speed steels, at the end of conventional heat treatment [7]. Rate of cooling and the presence of alloying elements depress the martensite start (M_s) temperature and martensite finish (M_f) temperature. At normal cooling rates, the martensite start (M_s) temperature is lowered by 20 ˚C.Cooling rates followed in case of hardening cycles, is much higher and hence the martensite start (M_s) temperature is further lowered. For eutectoid steel with 0.78 %C, transformation of martensite reaches its completion at approximately -50 ˚C. The following equations show the effect of alloying elements, in lowering martensite start (M_s) temperature.

$$Ms = 539 - 423(C) - 30.4(Mn) - 12.1(Cr) - 17.7(Ni) - 7.5(Mo) \ldots ˚C$$

$$Mf = Ms - 215 \ldots ˚C$$

Austenite is the softest phase and its presence in high speed steel cutting tools is detrimental to life of tools. Wear begins only at these soft spots, by ploughing action of hard particles in work piece material during metal removal [8].

Leskovsek [9] investigated the wear resistance of conventionally heat treated and cryogenically treated AISI M2 HSS. Wear volume was higher for samples that were conventionally heat treated than those subjected to deep cryogenic treatment at -196 ˚C. Also he confirmed that proper combination of hardness and fracture toughness is very essential apart from the cryogenic treatment in order to gain higher wear resistance.

Martensite transformed during cryogenic treatment is very hard and brittle and it is to be conditioned before usage. More over during transformation of austenite to martensite in the cryogenic treatment 4 % volumetric expansion occurs, which results in internal stresses. Hence double tempering at 150 – 200 ˚C for a period of 1.5 – 2 hours is very essential at the end of cryogenic treatment [9, 10].

Popandopulo and Zhukova [11] observed volumetric reduction of high speed steel specimen during cryogenic treatment in the temperature range of -90 to + 20˚C. Volumetric reduction was attributed to partial decomposition of martensite due to thermal instability and migration of carbon atoms to the neighboring lattice defects.

Akhbarizadeh [12] studied the wear resistance of cryogenically treated D6 tool steel by conducting sliding brasion wear test. He confirmed that shallow cryogenic treated specimens with 40 hours cycle exhibited better wear characteristics than those with 20 hours cycle. He attributed the improvement in wear resistance to reduction of austenite in case of shallow cryogenic treated specimens with 40 hours cycle than that with 20 hours cycle. He also observed that cryogenically treated specimens stabilized for a period of one week at room temperature performed better than non stabilized specimen in the wear test.

S.Kumar [13] used statistically designed experimental procedure to evaluate wear behavior of powder metallurgy composites. Response surface methodology was used to develop a mathematical model of wear behavior. Such a model could be used to predict, off-hand the effects of different factors on wear behavior.

In the present work, samples of AISI T42 HSS have been subjected to conventional heat treatment at hardening temperature of 1230˚ C. Subsequently the samples were subjected to deep cryogenic treatment at -195˚ C with a soaking time of 24 hours.

Sliding abrasion wear test was conducted on both conventionally heat treated specimens and deep cryogenic treated specimens to compare their wear behavior and to identify the mode and mechanism of wear. Discs made of En24 steel were used as counter face material to study the wear behavior of pin at different loads and sliding speeds.

2. Materials and Experimental Procedure

2.1. Material

High - speed steels are broadly classified as molybdenum based and tungsten based high- speed steels. AISI T42 is tungsten based high-speed steel with maximum of 10 % cobalt content. It is a special grade suitable for gear cutters, form tools and milling cutters. Any improvement in hardness and wear behavior due to cryogenic treatment, could add value to metal cutting operations and hence the specimens were prepared out of AISI T42 grade high-speed steel having the following nominal composition.

Table 1. *Chemical composition of AISI T42.*

Elements	% Weight	Elements	% Weight
C	1.5	Ni	0.422
Si	0.291	Co	9.75
Mn	0.232	Cu	0.147
P	0.023	Nb	0.012
S	0.005	Ti	0.007
Cr	4.21	V	>2.0
Mo	3.19	W	8.95

2.2. Conventional Heat Treatment

Conventional heat treatment was carried out in a barium chloride salt bath furnace as per the following sequence.

Preheating was done at 450˚C in FAC furnace for half an hour. Next stage of preheating was carried out in barium chloride salt bath furnace maintained at 950˚C for a period of 6 minutes. Finally the specimens were transferred to hardening furnace maintained at 1230˚C and soaked for a period of 40 seconds for austenitization to take place. Later the specimens were suddenly quenched in salt bath furnace maintained at 560˚C and soaked for a period of 20 minutes for stabilization of phases. Subsequently the specimens were air cooled up to room temperature.

The as quenched hardness was checked and it was found to be 64.2 to 65 HRC. To condition the martensite and to promote further transformation of carbides the specimens were triple tempered in salt bath furnace maintained at 540˚C with a soaking time of 90 minutes for each tempering cycle. Final hardness reached was found to be 66.8 to 67.2 HRC.

2.3. Deep Cryogenic Treatment

Since it is a comparative study on the effect of deep cryogenic treatment, on wear behavior, all the specimens at the end of conventional heat treatment were divided into two sets. Out of the two only one set was considered for deep cryogenic treatment.

And these specimens were loaded in the cryogenic treatment chamber and they were slowly cooled at a constant rate of -0.5˚C per minute until they reach -195˚C .Specimens were soaked at -195˚C for a period of 24 hours to allow for complete transformation reactions. Later, the specimens were warmed up at the rate of 0.5˚C per minute up to room temperature. To condition the martensite formed during deep cryogenic treatment and to promote precipitation of fine carbides the specimens were double tempered at 200˚C with a stabilization time of 2 hours for each cycle. The final hardness value at the end of deep cryogenic treatment and double tempering was found to be 69.5 to 70.2 HRC.

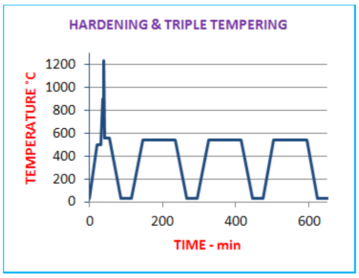


Fig. 1. *Conventional Heat Treatment Cycle for AISI T42.*

2.4. Preparation of Specimens

Ducom pin on disc wear tester with stationary pin and rotating disc configuration was used for conducting sliding abrasion wear study. The wear tests were conducted at a constant room temperature of 25˚C and relative humidity 60%, under dry condition. Cylindrical pins of diameter 10 mm with h7 tolerance and length 20mm were prepared from AISI T42 bar of 12 mm square cross section. Ends of the pin were polished using progressively finer grades of sand paper up to 1200 mesh. The weight of the specimens was recorded using a scale with precession of 10^{-5} gm, before loading them on wear tester. Discs of Ø55mm and thickness 10 mm with four holes of Ø3.5mm on pitch circle of Ø47 mm were made out of En 24 steel with C - 0.41%, Mn - 0.57%, Si - 0.24%, S - 0.01%, P - 0.03%, Cr - 1.21%, Ni – 1.47%, Mo – 0.28%. Surface of disc was polished to the same finish as that of pins, before conducting the wear study.

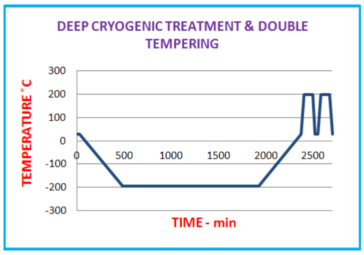


Fig. 2. *Deep Cryogenic Treatment Cycle for AISI T42.*

2.5. Design of Experiment

In order to investigate the wear behavior over a wide range of sliding velocity and normal load, response surface methodology was adopted. It is a statistical experimental design procedure that is very ideal, especially when the levels factors are more than two. Since, five levels of sliding speed and load were chosen for the experimental study a full, central composite design, with alpha value of 1.414 was used in designing the experiment. The centre point was replicated five times to account for experimental errors.

Initial screening tests were done to assess the probable range of the factors and constants. Since the disc used in the wear study was made out of plain En 24 with hardness of 14 HRC there was an appreciable amount of wear in pin material only for sliding distance above 1500 m-2000m. In order to make sure that the wear behavior of pin corresponds to steady state regime, the sliding distance was chosen to be 3000m for all the tests.

The lower and upper limits of sliding velocity was chosen between 0.4m/sec and 1.0 m/sec with a view to correlate the wear behavior of pin with the wear behavior of single point cutting tool. The lowest and highest limits of sliding velocity were decided based on the alpha value adopted in this experimental design.

Similarly the limits of normal load were decided based on earlier research carried out in similar wear studies. Wear tests were conducted as per the randomized order given in the design Table 4. For every run, the experiment was repeated twice and the weight loss of pin was recorded. The average value of weight loss was entered in the response column. The data obtained after conducting all wear tests was analyzed using analysis of variance (ANOVA) technique. According to this technique, the calculated value of F_{ratio} using the developed model, should not exceed the standard tabulated value of $F_{ratio,}$ for a desired level of confidence (95 %), for the model to be adequate.

Table 2. *Factors and their levels for sliding wear test.*

Factors	**Levels**				
	-1.414	**-1**	**0**	**+1**	**+1.414**
Sliding Velocity 'V' m/sec	0.28	0.4	0.7	1.0	1.2
Normal Load 'P' N	64.64	75	100	125	135.36

Table 4. *ANOVA for Weight Loss of Conventionally Heat Treated AISIT42 specimens.*

Source	**SS**	**df**	**MS**	**F**	**P-Value**
Model	1.468E-004	5	2.937E-005	56.55	<0.0001
A-Sliding Velocity	1.025E-004	1	1.025E-004	197.39	<0.0001
B-Load	1.983E-005	1	1.983E-005	38.19	0.0005
AB	1.560E-007	1	1.560E-007	0.30	0.6006
A^2	2.354E-005	1	2.354E-005	45.33	0.0003
B^2	2.316E-006	1	2.316E-006	4.46	0.0726
Residual	3.635E-006	7	5.193E-007		
Lack of fit	1.323E-007	3	4.409E-008	0.05	0.9830
Pure Error	3.503E-006	4	8.757E-007		
Cor Total	1.505E-004	12			

3. Results of Wear Test

Since it is a comparative study on the wear behavior of conventionally heat treated and deep cryogenic treated specimens the wear tests were carried out under identical conditions for both the cases. Design Expert v.7 was used in developing the experimental design and analysis of the data. The randomized order in which wear tests were conducted is given in table -3, along with weight loss of pin in the response column. The weight loss data obtained from wear test has been analyzed using ANOVA technique, for testing the adequacy of the developed model. Significance of the model terms and lack of fit were analyzed.

Table 3. *Experimental Design Table for pin –on –disc war test of Conventionally Heat Treated AISIT42 specimens.*

Run order	**Factor: 1 Sliding Velocity'V' 'm/sec'**	**Factor: 2 Normal Load'P' 'N'**	**Response Weight Loss 'gm'**
1	0.7	100	0.00595
2	0.4	75	0.00266
3	1.12	100	0.01415
4	0.28	100	0.00419
5	1.0	125	0.01286
6	0.7	100	0.00448
7	0.7	100	0.00489
8	0.7	64.64	0.00426
9	0.7	100	0.00539
10	0.4	125	0.00598
11	0.7	135.36	0.00903
12	0.7	100	0.00687
13	1.0	75	0.01033

Table 4 is the ANOVA output obtained using Design Expert software.

F_{ratio} calculated using the developed model is 0.05, which is less than tabulated value, $F_{0.05,\,3,\,4} = 6.59$. Therefore, lack of fit is not significant and the model is adequate. Hence the wear model can be used to navigate through space.

Wear Model in terms of actual factors:

$$\text{Weight Loss} = 8.26978 \text{x} 10^{-3} - 0.01405V - 1.03228 \text{x} 10^{-4} P - 2.63333 \text{x} 10^{-5} VP + 0.020439 V^2 + 9.232 \text{x} 10^{-7} P^2$$

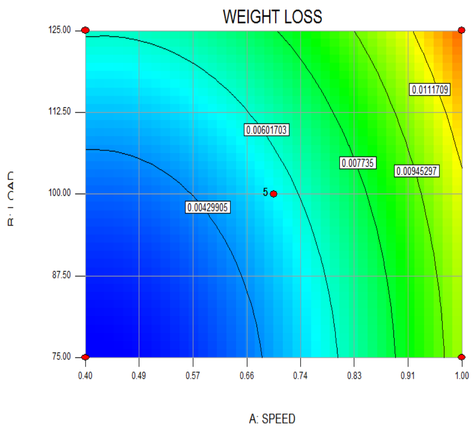


Fig. 3. *Response surface graph in 2D for weight Loss of Conventionally Heat Treated AISIT42 specimens.*

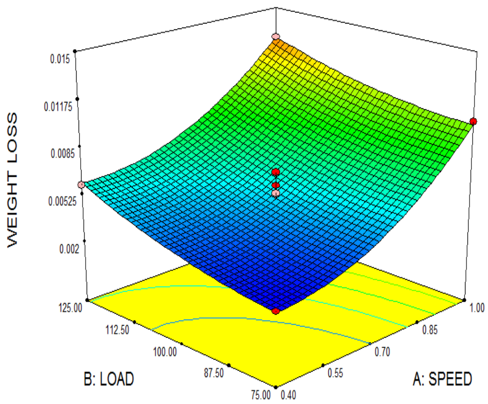


Fig. 4. *Response surface graph in 3D for weight Loss of Conventionally Heat Treated AISIT42 specimens.*

Table 5. *Experimental Design Table for pin –on –disc war test of Deep Cryogenically Treated AISIT42 specimens.*

Run order	Factor: 1 Sliding Velocity'V' 'm/sec'	Factor: 2 Normal Load'P' 'N'	Response Weight Loss 'gm'
1	0.7	100	0.00358
2	0.28	100	0.00298
3	1.0	75	0.00406
4	0.7	100	0.0034
5	0.7	64.64	0.00287
6	0.7	135.36	0.00578
7	0.7	100	0.00309
8	1.0	125	0.00634
9	1.2	100	0.00532
10	0.7	100	0.00376
11	0.4	125	0.0043
12	0.4	75	0.00226
13	0.7	100	0.00421

Table 6. *ANOVA for Weight Loss of Deep Cryogenically Treated AISI T42 specimens.*

Source	SS	df	MS	F	P-Value
Model	1.655E-005	5	3.311E-006	31.39	0.0001
A-Sliding Velocity	6.389E-006	1	6.389E-006	60.57	0.0001
B-Load	8.894E-006	1	8.894E-006	84.33	<0.0001
AB	1.440E-008	1	1.440E-008	0.14	0.7227
A^2	5.133E-007	1	5.133E-007	4.87	0.0632
B^2	8.972E-007	1	8.972E-007	8.51	0.0225
Residual	7.383E-007	7	1.005E-007		
Lack of fit	4.046E-008	3	1.349E-008	0.077	0.9690
Pure Error	6.979E-007	4	1.745E-007		
Cor Total	1.729E-005	12			

F_{ratio} calculated using the developed model is 0.077, which is less than tabulated value $F_{0.05,3,4} = 6.59$. Therefore, lack of fit is not significant and the model is adequate. Hence the wear model can be used to navigate through space

Wear Model in terms of actual factors:

$$\text{Weight Loss} = 5.08997\text{x}10^{-3} - 2.04642\text{x}10^{-3}\,V - 7.83432\text{x}10^{-5}P + 8\text{x}10^{-6}VP + 3.01806\text{x}10^{-3}\,V^2 + 5.746\text{x}10^{-7}P^2$$

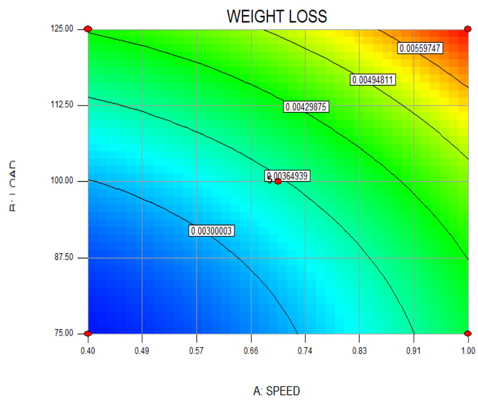


Fig. 5. *Response surface graph in 2D for weight Loss of Cryogenically Treated AISIT42 specimens.*

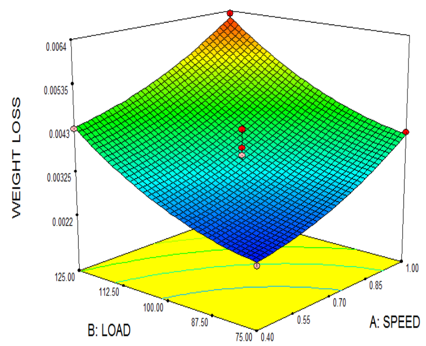


Fig. 6. *Response surface graph in 3D for weight Loss of Cryogenically Treated AISIT42 specimens.*

Based on the predictive model for weight loss, the wear rates wear calculated within the range of sliding velocity and load used in this study. Fig-7 shows the effect of sliding velocity on weight loss of pin at different loads. For a normal load of 125N at sliding velocity 0.4m/sec weight loss of CHT specimen is 1.42 times that of DCT specimen. At sliding velocity of 1.2 m/sec and normal load of 125N the weight loss of CHT specimen is found to be 2.49 times that of DCT specimen. The trend of wear of CHT specimen suggests that wear increases rapidly as sliding velocity increases. On the other hand the trend of DCT specimen shows a moderate increase in wear with respect to sliding velocity.

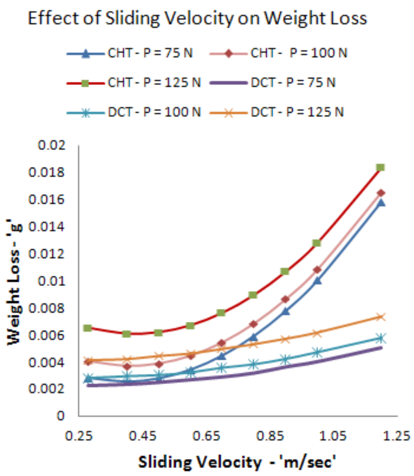


Fig. 7. Comparison of weight loss of AISI T42 pins subjected to Conventional Heat Treatment (CHT) and Deep Cryogenic Treatment (DCT) under sliding abrasive wear test.

Making reference to figure-8, where the effect of normal load on wear behavior obtained from the model is presented. The main inference made is that normal load is comparatively a less sensitive factor than sliding velocity as far as wear is concerned. At normal load of 75N and sliding velocity of 1.0m/sec weight loss of CHT specimen is 2.51 times that of DCT specimen. At a higher load of 125 N and sliding velocity 1.0 m/sec the weight loss of CHT specimen is 2.06 times that of DCT specimen.

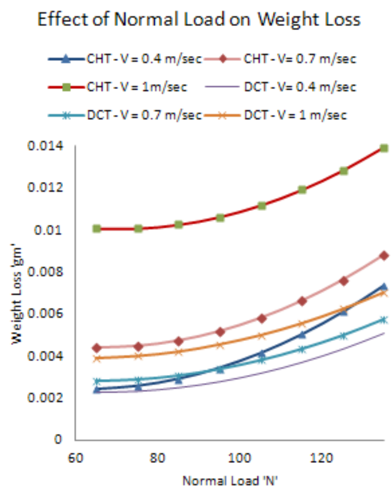


Fig. 8. Comparison of weight loss of AISI T42 pins subjected to Conventional Heat Treatment (CHT) and Deep Cryogenic Treatment (DCT) under sliding abrasive wear test.

4. Wear Rate

The wear rate was calculated in terms of wear volume (mm^3) per unit force (N) and unit distance (m).Since the break in period, is found to be less than 7%of the total distance of 3000 m. Hence the accelerated wear during break in period is considered negligible.

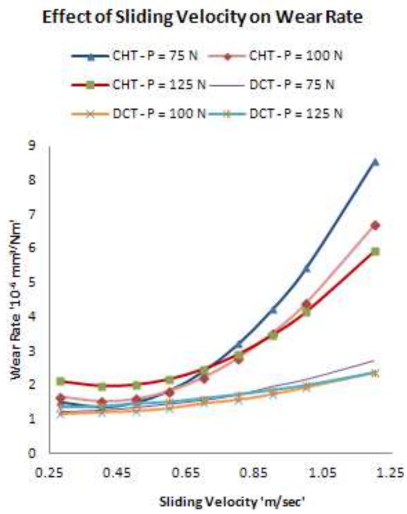


Fig. 9. Comparison of weight loss of AISI T42 pins subjected to Conventional Heat Treatment (CHT) and Deep Cryogenic Treatment (DCT) under sliding abrasive wear test.

The wear rate was calculated based on the weight loss, over the entire sliding distance of 3000m, neglecting the effect of unsteady state wear during the break in period [14]. Wear rate was calculated using the expression

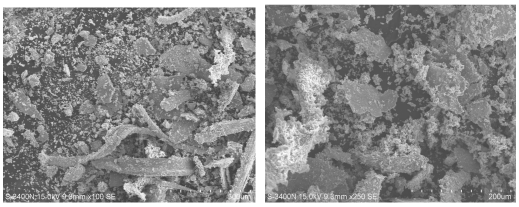
$$Wr = \frac{\Delta m}{\rho LF} \times 1000$$

In this expression Wr is the wear rate expressed in 'mm3/Nm'; Δm - weight loss of pin in g; ρ = 8.23, density of AISI T42 HSS in 'g/cm3';L=3000, sliding distance in 'm' and F- normal load in 'N'.

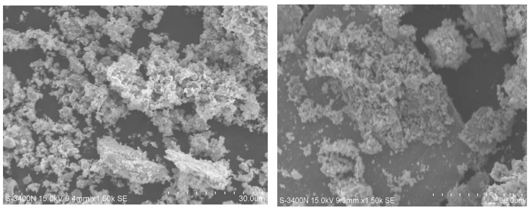
5. Morphology of Worn Surface and Wear Debris

5.1. SEM Analysis of Wear Debris

SEM images of wear debris, corresponding to steady state wear regime, were taken at 2500X magnification to analyze the mode and mechanism of wear. Fig. 10 is a representative sample of image of wear debris corresponding to CHT specimen. The image assists to infer that the disc material underwent plastic deformation under the cyclic shear stress and got peeled off from the substrate by delamination mechanism. There is enough evidence of severe plastic deformation of disc material.



A B



C D

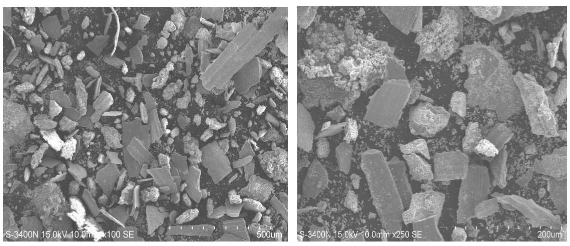
Fig. 10. *SEM image of Wear Debris of CHT in specimen at sliding velocity of 0.4m/sec and normal load of 75N.*

Due to cyclic nature of shear stress that acted on disc, the plastically deformed disc material was removed by delaminative wear mechanism.

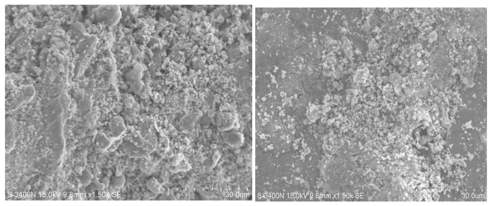
The presence of loose oxide particles in scattered form and also in agglomerated form was identified. The presence of oxide particles is comparatively higher in the wear debris pertaining to wear of CHT specimens. These oxide particles originated from pin surface by breakaway of oxide layer during the wear test.

These oxide particles adhere to the surface of pin as well as rotating counter face. Compact oxide layer formed during wear test on the face of pin and loose oxide particles trapped at the interface between the pin and disc, prevent direct metal to metal contact and reduce the frictional force.

In case of images of wear debris corresponding to DCT specimen, shown in Fig. 11, majority of the oxide particles was found to be in scattered loose form. Energy dispersive X-ray micro analysis of wear debris was made to confirm the elements present in the debris and to cull out the mechanism of wear. Referring Fig. 12 to Fig. 17, the presence of ferrous oxides was confirmed from the wear debris of CHT and DCT specimens. The semi quantitative analysis of wear debris using EDS reveals that the presence of iron – oxides was comparatively high in the case of wear debris generated by CHT specimen than DCT specimen, during the sliding abrasive wear test.



E F



G H

Fig. 11. *SEM image of Wear Debris of DCT in specimen at sliding velocity of 0.4m/sec and normal load of 75N.*

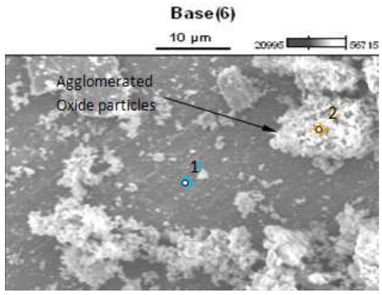


Fig. 12. *SEM image of wear debris of CHT specimen at 2500X for sliding velocity of 0.4m/sec and normal load of 75N.*

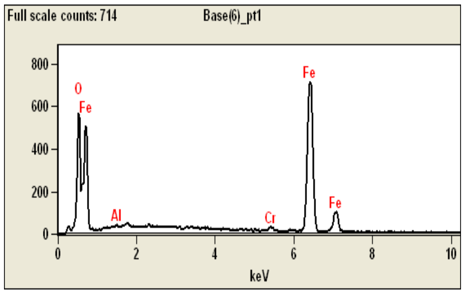


Fig. 13. *SEM - EDS Spectrum at point 1of Fig. 12.*

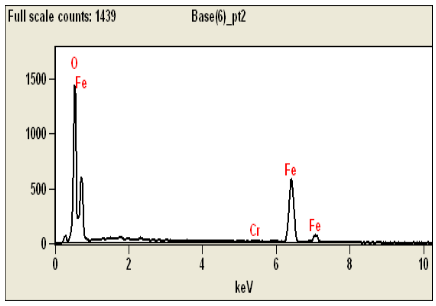


Fig. 14. *SEM - EDS Spectrum at point 2of Fig. 12.*

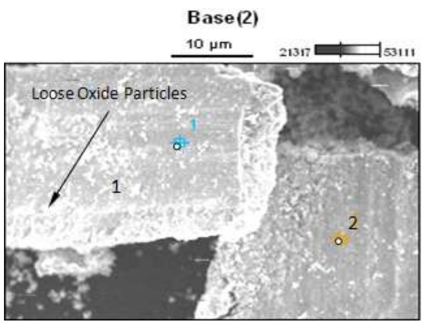


Fig. 15. *SEM image of wear debris of DCT specimen at 2500X for sliding velocity of 0.4m/sec and normal load of 75N.*

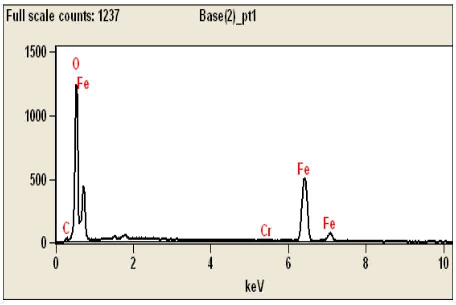


Fig. 16. *SEM - EDS Spectrum at point 1of Fig. 15.*

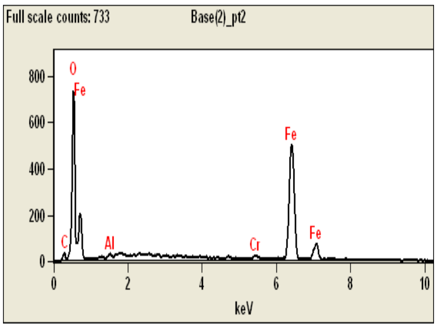


Fig. 17 *.SEM - EDS Spectrum at point 2of Fig. 15.*

5.2. Mode and Mechanism of Wear

The topography of worn surface was analyzed using scanning electron microscope to study the extent of surface damage and to identify the mode and mechanism of wear. Representative samples of SEM images of worn pin surface taken at 500X and 2500X magnification are presented here. The images at the left hand side correspond to CHT specimen and those at the right hand side correspond to DCT so as to compare and contrast the effect of cryogenic treatment on the wear behavior.

The maximum wear rate observed in the present study corresponds to that of CHT specimen and its value is found to be less than $9x10^{-9}$ mm^3/N.mm. Wang et al [15] in an earlier research suggested that for steel specimens, the upper limit of wear rate for mild oxidative wear is 1x10 $^{-8}$ mm^3/N.mm. And the lower limit of wear rate for severe delaminative wear is 2x10 $^{-8}$ mm^3/N.mm. Also the author indicated that the term transition wear could be used if wear rate lies between 1-2 x10 $^{-8}$ mm^3/N.mm.

Also Lim et al [16] reported that for steel specimens mild oxidative wear occurs at sliding velocity just above 1m/sec and moderate values of normal load. Mild oxidative wear occurs event at sliding velocity of 0.5 m/sec for higher values of normal load. The wear mode shifts to severe oxidative wear at sliding velocity of 10m/sec and above.

The maximum value of sliding velocity encountered in the present study is 1.2m/sec and also the maximum amount of wear rate encountered in the present study is well below the upper limit of wear rate for mild oxidative wear. The above information assists to infer that the wear mechanism encountered in the present study corresponds to mild oxidative wear.

As the present wear study has been carried out in dry sliding abrasion configuration open to atmosphere, transactions occurred at the interface between pin and disc. The bulk heating effect was negligible in the mild oxidative regime and only flash heating occurred at asperities that come in contact at the interface. The increase in temperature in this case was confined to only asperities. Once the temperature at the asperities reached a value high enough to cause oxidation, formation of oxide layers took place.

Referring to Fig. 18, at sliding velocity of 0.4m/sec and normal load of 75 N, a lot of contrast in wear behavior could be noticed. Compact oxide layers are found in both CHT and DCT specimens. Intergranular wear grooves are identified and a number of voids created by pull out of primary carbides (PCs) are observed in oxide depleted areas of CHT specimen (C-CHT). Whereas the surface of DCT specimen presents a very smooth texture at magnification of 2500X (D-DCT).

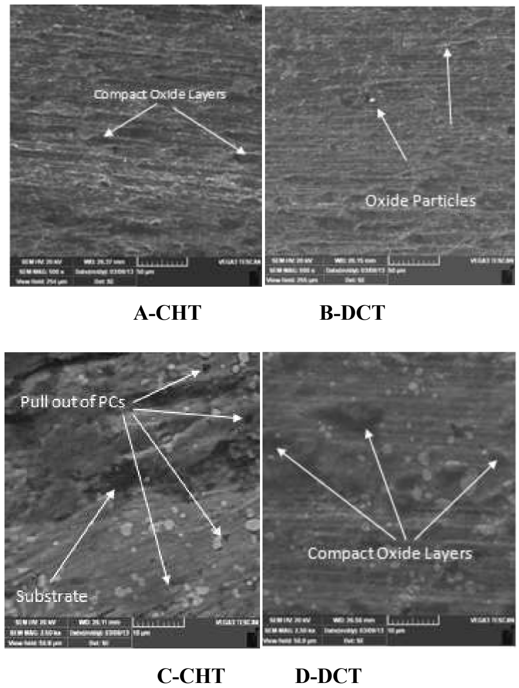
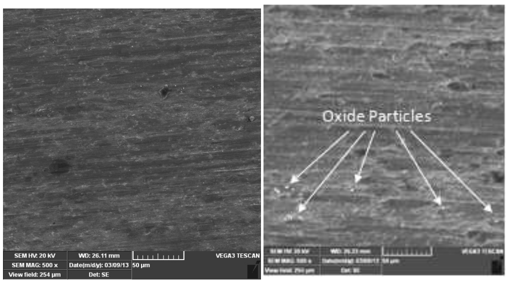
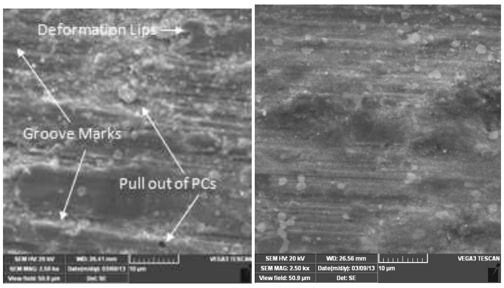


Fig. 18. *SEM image of worn surfaces of pins subjected to Conventional Heat Treatment(A&C) and Deep Cryogenic Treatment (B&D) for Sliding Velocity = 0.4 m/sec & Normal Load = 75N.*

Making reference to Fig. 19, for sliding velocity of 0.4m/sec and normal load of 125N, there is noticeable amount of plastic deformation of oxide layers stretched in the direction of sliding (G-CHT). Deformation has been caused by increase in normal load. The breakaway of oxide layers has occurred and fine fragments of loose oxide particles are noticeable in CHT specimen. Formation of new oxide layers consequent to the breakaway of older oxide layer is observed in CHT specimen (G-CHT). In case of CHT specimen number of voids (G-CHT) due to pull out of carbides is visible but the number of such voids (H-DCT) are comparatively lesser in the DCT specimen than CHT specimen.



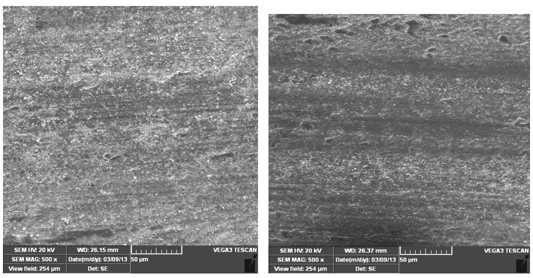
E-CHT **F-DCT**



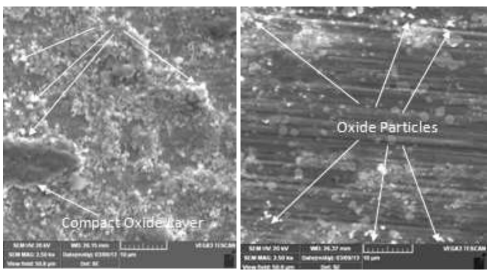
G-CHT **H-DCT**

Fig. 19. *SEM image of worn surfaces of pins subjected to Conventional Heat Treatment(E&G) and Deep Cryogenic Treatment (F&H) for Sliding Velocity = 0.4 m/sec & Normal Load = 125N.*

Referring to Fig. 20, for a sliding velocity of 1.0 m/sec and normal load of 75N, presence of fine particles of broken oxide layers across the entire field, is clearly noticed (I-CHT). At a magnification of 2500X, the extent of surface deterioration is found to be higher (K-CHT). Population of loose oxide particles due to the breakaway of oxide layer is also higher. For the same combination of sliding velocity and normal load, DCT specimen exhibits excellent surface integrity (L-DCT) and extent of surface damage is far less compared to CHT specimen.



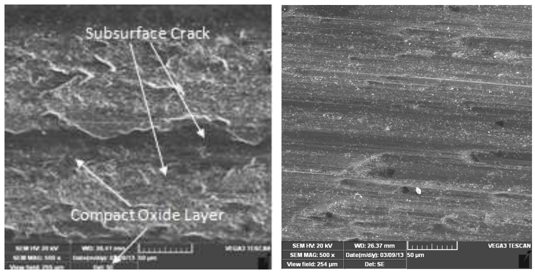
I-CHT **J-DCT**



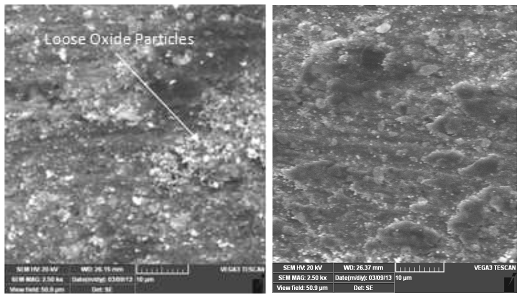
K-CHT **L-DCT**

Fig. 20. *SEM image of worn surfaces of pins subjected to Conventional Heat Treatment(I&K) and Deep Cryogenic Treatment (J&L) for Sliding Velocity = 1.0 m/sec & Normal Load = 75N.*

Referring to Fig. 21, at sliding velocity of 1.0 m/sec and normal load of 125N the SEM image (M-CHT) taken at 500X magnification shows a extremely different wear behavior between CHT and DCT specimens.



M-CHT **N-DCT**



O-CHT **P-DCT**

Fig. 21. *SEM image of worn surfaces of pins subjected to Conventional Heat Treatment(M&O) and Deep Cryogenic Treatment (N&P) for Sliding Velocity = 1.0 m/sec & Normal Load = 125N.*

Extent of deformation of compact oxide layer is higher and completely different from the previous case. Deformation lips and sub surface cracks are clearly visible even at 500X magnification. Deformation lips stretched in the sliding direction clearly indicates that sever plastic deformation has occurred in this case. This is mainly due to the increase in normal load coupled with increase in sliding velocity.

Whereas the image of DCT specimen at 500X (N-DCT) indicates only mild patches of compact oxide layers whose size is far lesser than that of CHT specimen. Image (O-CHT) at 2500X shows presence of many voids due to pull out of carbides, presence of loose oxide particles in scattered and agglomerated form in CHT specimen. But in the DCT specimen voids due to pull out of primary carbides (PCs) are comparatively less (P-DCT). Deformation of compact oxide layers in the direction of sliding and breakaway of oxide particles from the deformation lips is clearly observed. Population of such loose oxide particles is also comparatively less (P-DCT) in DCT specimen.

6. Discussions

There will be some form of transactions, at the interface between the disc and the surface of the pin in contact, during sliding abrasive wear test. Transactions do occur between the environment and the sliding surfaces because the wear test has been conducted under dry condition exposed to atmosphere. Normally any ferrous material tends to react more so due to the presence of alloying elements, oxygen present in the atmosphere in the presence of heat generated due to friction between asperities. AISI T42 is a high alloy steel and hence there was more scope for thermo chemical transactions at the interface. Bulk heating is negligible in mild oxidative wear mode. Only flash heating, occurred, confined to vicinity of asperities that come in contact. Oxidation took place at the contact points of asperities, leading to formation of tribo-oxide layers, usually Fe_3O_4 and Fe_2O_3 .Oxide layers prevent metal to metal contact and thereby reduce frictional coefficient at the interface.

Under the action of shear stress the oxide layers were subjected to plastic deformation and crack. Breakaway occurred only at deformation lips when the substrate can no longer supported the oxide layer above it. Formation and breakaway of oxide layers is a continuous process whose dynamics were largely affected by sliding velocity, normal load, temperature, chemical affinity and nature of atmosphere. When breakaway depleted oxide layers, formation of fresh oxide layers replenished it.

Based on the wear rate and the sliding velocity used in the present study the mode and mechanism of wear has been identified as mild oxidative. Out of the two factors sliding velocity and normal load the former is found to be very sensitive as far as wear is concerned. The Fig. 7 shows a drastic increase in wear rate of CHT specimens at sliding velocity of 1m/sec and the difference further expands with increase in sliding velocity.

These results corroborate well with the SEM image (Fig. 21.O-CHT) of CHT specimen taken at 500X and 2500X.

Similarly at sliding velocity of 0.4 m/sec and load of 75N, referring to Fig. 7, it is clearly evident that the difference wear between CHT and DCT specimen is comparatively less. Also the SEM images taken at 500X in Fig. 18, shows more or less a similar surface character between CHT and DCT specimens.

The wear behavior of CHT specimen is characterized by voids created due to pull out of carbides and groove marks. In majority of the observations, loose oxide particles generated due to breakaway of oxide layers was found in scattered as well as agglomerated form.

On the other hand wear behavior of DCT specimen shows entirely different character. Referring to Fig. 7 , the slope of the curve is almost steady over the entire range of sliding velocity used in the present study. Corresponding to sliding velocity of 1m/sec and normal load of 125 N the SEM images shows very rare cases of pull out of carbides. Also the presence of loose oxide particles is very minimal. The above information assist to infer that wear resistance of DCT specimens is quite high compared to CHT specimen.

The presence of austenite in CHT specimen is the prime reason for the poor wear resistance exhibited by the specimen. Presence of austenite is inevitable in CHT specimens especially when the alloying elements are in higher proportion. Since AISI T42 HSS is a high alloy steel, the presence of austenite at the end of conventional heat treatment is mathematical certainty. Austenite being the softest phase present in the CHT specimen, wear took place only at these sights by ploughing action of hard asperities available in counter face.

In the DCT specimen there was no trace of austenite. Apart from the above fine carbides of size less than 0.1μ precipitated during the low temperature tempering at the end of cryogenic treatment, strengthened the martensite matrix by dispersion hardening. The above transformations that occurred during cryogenic treatment gave rise to increase in hardness value from 67 HRC at the end of CHT to 69HRC.Improvement in wear resistance of DCT specimen is mainly due to the above transformations that occurred in microstructure and hardness.

Under the test conditions used in the present study deep cryogenically treated AISI T42 HSS tool material exhibits higher wear resistance compared to conventionally heat treated specimens. Also there was an improvement in hardness value form 66.8-67.2 HRC at the end of conventional heat treatment to 69.5-70.2 HRC at the end of deep cryogenic treatment. The predictive model developed using response surface methodology corroborates well with the SEM images of worn surface of pin specimen. The benefits of DCT increases with increasing velocity, within the range of sliding velocity used in the present study. Wear rate of CHT specimen was 3.138 times the wear rate of DCT specimen, for sliding velocity of 1.2 m/sec and normal load of 75N.

Similarly at sliding velocity of 1.2m/sec and normal load of 125 N wear rate of CHT specimen was 2.493 times that of DCT specimen. The mode and mechanism of wear has been identified as mild oxidative, within the range of factors used in the present study.

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