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Effects of Cryogenic Treatment, Hardening and Multiple Tempering On Wear Behavior of D6 Tool Steel

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---ABSTRACT---

This experimental work intended to investigate the effects of cryogenic treatment on the wear behavior of D6 tool steel. For this purpose, the temperature was used -185°C as deep cryogenic temperature. The effects of cryogenic temperature (deep), cryogenic time (kept at cryogenic temperature for 36 hr) on the wear behavior of D6 tool steel were studied. The findings showed that the cryogenic treatment decreases the retained austenite and hence improves the wear resistance and hardness. Due to more homogenized carbide distribution as well as the elimination of the retained austenite, the deep cryogenic treatment demonstrated more improvement in wear resistance and hardness compared with the conventional heat-treatment. By increasing the keeping time at cryogenic temperatures, more retained austenite was transformed into martensite; thus, the wear resistance was improved and further hardness were observed.This experimental work also intended to investigate the role of multiple tempering before and after cryogenic treatment on friction and wear behaviour of D6 tool steel as classified by American Iron and Steel Institute (AISI). D6 tool steel is used for measuring tools, blanking dies, forming dies, coining dies, long punches, forming rolls, edging rolls, master tools, extrusion dies, drawing dies, moulds for pressing abrasive powders etc.The different combination of heat treatments like hardening (at 1020°C) for one hour, tempering (at 210°C) for two hours and deep cryogenic treatment (at -185°C) for 36 hours was done on D6 tool steel. Wear test were performed using pin-on-disc wear tester to which two different normal loads (3.1Kg and 5.1Kg) and two different velocities (1.5m/s and 2.5m/s) were applied. Hardness of specimens was measured by using Rockwell Hardness tester. Microstructural characterizations of the differently heat treated specimens have been done by image analyzer software with inverted microscope.The findings show that the cryogenic treatment improves the wear resistance and hardness of D6 tool steel. The results indicate that, in HCT specimens there was large reduction in the wear rate and markedly enhancement in wear resistance of the D6 tool steel.

KEYWORDS: *- AISI D6 tool steel, cryogenic treatment, wear rate and wear resistance.*

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I. INTRODUCTION

To understand the effects of cryogenic processing it is essential that one can be acquainted with the heat treating of metals. The primary reason for heat treating steel is to improve its wear resistance through hardening. Gears, bearings, and tooling for example are hardened because they need excellent wear resistance for extended reliability and performance [1].

Cryogenic processing (CP) is presently employed in the fields like aerospace and manufacturing industries, sports and music instruments, firearms etc. for performance enhancement of various components. In the last decade, a good number of investigations have been directed to improve the tribological properties like wear resistance of tool/die steels by cryotreatment. Cryogenic treatment of tooling steels is a proven technology to increase wear resistance and extend intervals between component replacements for dies, punches, drill bits, end mill cutters, bearings, cams, crankshafts, blocks, pistons, blades etc. Controlled CP is commonly appended in-between conventional hardening and tempering treatments for tool/die steels [2]. The execution of the deep cryogenic treatment on quenched and tempered high speed steel tools increases hardness, reduces tool consumption and down time for the equipment set up, thus leading to cost reductions of about 50% [3].In last few years it is found that the use of combination of different heat treatment like hardening, multiple tempering and cryogenic treatments affect on the friction and wear behaviour of AISI D6 tool steel [4].

II. AISI D6 TOOL STEEL

Tool steels were developed to resist wear at temperatures of forming and cutting applications. Tool steel is used on a wide variety of applications where resistance to wear, strength, toughness and other properties are selected for optimum performance. They are broadly divided into six categories: cold work, shock resisting, hot work, high speed, mold and special-purpose tool steels [1].Generally speaking, many tool steels fulfill the requirements for a given application, so that final selection is guided by considering the tool life as well as the cost of material and fabrication. First reasonable factor affecting the tool life is adhesion wear [1]. The high-carbon, high-chromium cold work tool steel, designated as group D (Deep Hardening) steel in the AISI classification system, are the most highly alloyed cold-work steel. The high-carbon, high-chromium cold work D6 tool steel has extremely high wear and abrasion resistance. Again, the high alloy content provides excellent hardenability and good dimensional stability. D6 tool steel contributes approximately 21% of total tool steel application. Although the high abrasion resistance of the D6 tool steels is desirable for cold-work applications, the machining and grinding operations during manufacturing of finished dies and molds are difficult.

A. Applications of D6 Tool Steel

Measuring tools, blanking dies, forming dies, coining dies, slitting cutters, heading tools, long punches, forming rolls, edging rolls, master tools, beading rolls, intricate punches, extrusion dies, drawing dies, lamination dies, thread rolling dies, shear blades, burnishing tools, gauges, knurls, wear parts, plastic moulds, decorative knives, hunting knives, mill rolls, spinning tools, moulds for pressing abrasive powders etc.

III. LITERATURE REVIEW

In tool steels, a low percentage of austenite is retained after the conventional heat-treatment named ‘‘retained austenite”. The retained austenite as a soft phase in steels could reduce the product life and, in working conditions, it can be transformed into martensite. This new martensite could cause several problems for working tools. This new martensite is very brittle and differs from the tempered one, which is used in tools. Furthermore, this martensite causes micro cracks and reduces the product life. Moreover, the retained austenite-to-martensite transformation provides dimensional instability.

Regarding the problems mentioned above, the controlled transformation of the retained austenite into martensite is essential to many types of component. In order that this transformation occurs, the cryogenic treatment is used. As a result, the retained austenite is reduced and higher wear resistance is obtained. Two types of cryogenic treatment are usually applied as follows: (1) the shallow cryogenic treatment (SCT) is performed between -50^{o}C and -100 ^{o}C after quenching. In SCT, the retained austenite is reduced and higher wear resistance is obtained in tool steels; (2) the deep cryogenic treatment (DCT) is conducted at the temperatures below -125^{o}C. This treatment reduces or eliminates the retained austenite and distributes carbides in a higher proportion and in a more homogenized manner. Accordingly, further wear resistance as compared with SCT was observed. At DCT temperatures, austenite and martensite lattice is contracted. As a result of this contraction, carbon atoms are forced to diffuse. At higher temperatures, these carbon atoms would produce the new carbides, thereby leading to more homogenized carbide distribution [1-10].

A. Akhbarizadeh et.al [8] studied the effects of cryogenic treatment on the wear behavior of D6 tool steel. For this purpose, two temperatures were used: -63ºC as shallow cryogenic temperature and -185ºC as deep cryogenic temperature. The effects of cryogenic temperature (Shallow and deep), cryogenic time (kept at cryogenic temperature for 20 hours and 40 hours) and stabilization (kept at room temperature for one week) on the wear behavior of D6 tool steel were studied. Wear tests were performed using a pin-on-disk wear tester. Due to more homogenized carbide distribution as well as the elimination of the retained austenite, the deep cryogenic treatment demonstrated more improvement in wear resistance and hardness compared with the shallow cryogenic treatment. By keeping the samples for a period of one week at room temperature after quenching (stabilization), more retained austenite was transformed into martensite and higher wear resistance and higher hardness were achieved.

B. Summary of Literature Review

Recent studies have indicated that cryogenic treatment is an essential supplementary treatment, which is performed on products after conventional heat-treatment in order to increase their wear resistance in some materials and to produce dimensional stability in others. The cryogenic treatment is conducted on tool steels, maraging steel, cast iron, carburized steel, tungsten carbide, polymers and composites. In all of the materials mentioned, the cryogenic treatment increases the wear resistance and subsequently increases the product life. The cryogenic treatment has been used as a finishing process in the past few decades. This process is also being used in aircraft and automobile industries as well as many other areas.Over the last decade, several researchers [1–10] have reported that the Deep Cryogenic Treatment (DCT) considerably improves the wear resistance (WR) of AISI D6 tool steels than those obtained either by Cold Treatment (CT) or by Conventional Heat Treatment (CHT). Also it is found that the considerable reduction in wear rate (W_R) and coefficient of friction (μ).In addition, it has also been reported that DCT and multiple tempering after cryogenic treatment enhances the dimensional stability and reduces the residual stresses. These favourable effects increase the service life of the components made of AISI D6 tool steels.

Literature of past work does not adequately clarify the selection of tempering, cryogenic temperature and soaking time. There is a need to standardize the process for cryogenic treatment in particular tool steels and understand the underlying metallurgical mechanism responsible for improvement of wear. In general cryogenic treatment and multiple tempering is still in the dormant level as far as wear rate, wear resistance and coefficient of friction is concerned. This is the main focus of the present work on D6 tool steel.

C. Problem Definition

Effects of cryogenic treatment on wear behavior of D6 tool steel and effect of multiple tempering before and after the cryogenic treatment.

D. Objectives

Therefore the present investigation is based on the effect of cryogenic treatment on friction and wear behaviour of AISI D6 tool steel and has following objectives,

1) To study the effect of wear test parameters like normal load, velocity of counter disc on friction and wear behaviour of D6 tool steel.
2) To study the effect of different heat treatments like hardening, cryogenic treatment and multiple tempering on wear volume, coefficient of friction, wear rate and wear resistance of D6 tool steel.
3) To study the relationship between normal loads, velocity of counter disc, coefficient of friction, wear rate and wear resistance.
4) To find percentage improvement in wear resistance due to combination of different heat treatments on D6 tool steel.
5) It is intended that, this research will be useful in promoting the applications of cryogenic treatment on D6 tool steel.

E. Proposed Experimental Work

For improvement of friction and wear behaviour of AISI D6 tool steel, combination of different heat treatments like hardening, multiple tempering, cryogenic treatments are used. In this study hardening temperature 1020°C for one hour, tempering temperature 210°C for two hours, cryogenic temperature -185°C for 36 hours, soft tempering temperature 100°C for one hour were selected. The reduction in wear rate, coefficient of friction; improvement in wear resistance of specimens were assessed by a pin-on-disk wear testing machine. For wear test the disc are made of EN-35 (68 HRC maintained) of surface roughness, Ra = 0.5 μm. Testing conditions were used as follows,

a. Normal Load, FN = 3.1Kg, 5.1Kg
b. Sliding speed, V = 1.5, 2.5 m/s
c. Test Duration, T = 60 Min.

Change in hardness of specimens was measurement by using Rockwell Hardness tester. Microstructural characterizations of the differently heat treated specimens have been done by image analyzer software with inverted microscope.

IV. EXPERIMENTAL DETAILS

To ensure a high-quality product, diagrams and lettering MUST be either computer-drafted or drawn using India ink.

a. Material

The present investigation has been conducted with samples of AISI D6 tool steel. AISI D6 tool steel is also designated as T30405 by Unified Numbering System. The round bars of diameter 9.20mm were selected for this experimentation. The specimens for wear test were prepared of diameter 9.20mm and height 30mm. For hardness test specimens were prepared of diameter 9.20mm and height 10mm. The chemical composition of specimens has analyzed by Optical Emission Spectrometer (ASTM-E-1066-2008). Table no. 4.1 conforms to the chemical composition of AISI D6 tool steel.

Table no. 4.1 Chemical Composition of D6 Tool Steel

Sr. No.	Element	Weight Percentage	
		Actual %	AISI Specification of D6 Tool Steel
1	C	2.16	2.00-2.35
2	Mn	0.38	0.60 Max.
3	Si	0.35	0.30-0.50
4	S	0.011	0.030 Max.
5	P	0.015	0.030 Max.
6	Cr	12.02	11.00-13.00
7	Mo	Nil	--
8	W	0.23	1.00 Max.

b. Treatments

The material selected for this work was given various treatments and treatment combinations indicated in Table no. 4.2.

4.1.Hardening

The first step in the heat treatment of AISI D6 tool steel was hardening. The purpose of hardening was to harden steel to increase the wear resistance, cutting ability. Hardening of AISI D6 tool steel was done in the tubular furnace (3.5KW, 230V AC, 15A, 1200±10°C) at a temperature of 1020°C [1, 6] for 1 Hour. During hardening process, inert gas Argon was supplied in tubular furnace to avoid oxidation. Harden AISI D6 tool steel followed air cooling which provides great benefit of minimizing distortion and dimensional changes [11].

Table no. 4.2 Different Heat Treatments Employed to AISI D6 tool steel

Sr.No.	Nomenclature	Particulars of Treatment
1	HT	Hardening (1020°C for 1 Hr), Single Tempering (210°C for 2 Hr)
2	HTT	Hardening (1020°C for 1 Hr), Double Tempering (210°C for 2 Hr)
3	HTTT	Hardening (1020°C for 1 Hr), Triple Tempering (210°C for 2 Hr)
4	HCT	Hardening (1020°C for 1 Hr), Cryotreated (-185°C for 36 Hr), Single Tempering (210°C for 2 Hr)
5	HCTT	Hardening (1020°C for 1 Hr), Cryotreated (-185°C for 36 Hr), Double Tempering (210°C for 2 Hr)
6	HCTTT	Hardening (1020°C for 1 Hr), Cryotreated (-185°C for 36 Hr), Triple Tempering (210°C for 2 Hr)
7	HCST	Hardening (1020°C for 1 Hr), Cryotreated (-185°C for 36 Hr), Soft Tempering (100°C for 1 Hr)
8	HTCST	Hardening (1020°C for 1 Hr), Single Tempering (210°C for 2 Hr), Cryotreated (-185°C for 36 Hr), Soft Tempering (100°C for 1 Hr)
9	HTTCST	Hardening (1020°C for 1 Hr), Double Tempering (210°C for 2Hr), Cryotreated (-185°C for 36 Hr), Soft Tempering (100°C for 1Hr)
10	HTTTCST	Hardening (1020°C for 1 Hr), Triple Tempering (210°C for 2 Hr), Cryotreated (-185°C for 36 Hr), Soft Tempering (100°C for 1 Hr)

4.2.Tempering

The process which consists of heating the hardened components to a temperature between 100°C and 700°C, holding at this temperature for specific period and cooling to room temperature, usually by air is called as 'tempering'.The purposes of tempering are as follows,

a. To relieve the internal stresses developed due to rapid cooling of steels after hardening process and due to volume changes occurring in the austenite to martensite transformation, to reduce brittleness,
b. To reduce hardness and to increase ductility and toughness,
c. To eliminate retained austenite [12].

Tempering of D6 tool steel was done in the muffle furnace (3.8KW, 230V AC, 600±10°C). Samples of treatment HT, HTT, HTTT, HCT, HCTT, HCTTT, HTC, HTTC and HTTTC after H and HC were immediately subjected to tempering at temperature of 210°C with 2 Hr soaking time, followed by air cooling to room temperature, that is, single tempering. After the air cooling the remaining samples were subjected to double tempering for the same temperature and time and then air cooled. Similar procedure is again followed for triple tempering on the remaining samples from double tempering. The detailed heat treatments are indicated in Table no. 3.2.

4.3.Cryogenic Treatment

The cryogenic treatment was done in Cryoprocessor system at Nashik Cryogenic Services,Nashik.

Fig.4.1 Cryoprocessor Setup

Cryoprocessor is capable of maintaining shallow subzero treatment, deep subzero treatment and cryogenic subzero treatment temperatures for any length of time through software based program which control the flow of liquid nitrogen via solenoid valve as per the demand of programming logic controller. The arrangement of cryoprocessor is as shown in Fig. 4.1. As soon as liquid nitrogen enters into Cryoprocessor, it gasifies immediately through multi hole slitter and thus cooling of the specimen takes place. Temperature of the bath is sensed using Resistance Temperature Detector, which provides online feedback of temperature of the bath to regulate the flow of liquid nitrogen.

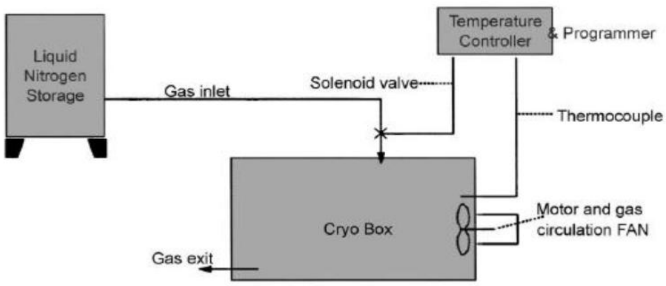


Fig. 4.2 Block Diagram of Cryoprocessor

Schematic line diagram of Cryoprocessor used in this experiment is as shown in Fig. 4.2. In the present work, the specimens were cryotreated at -185°C, the soaking time was selected 36 Hr [7]. The bath was allowed to cool down slowly (3- 4°C/ min) to avoid thermal shocks.Once the subzero treatment was over, all the specimens were allowed to warm up in an insulated thermocol box which takes normally 16-24 hr to reach the room temperature depending on the treatment given. A computer generated thermal profile of the processor is shown in Fig. 4.3. Blue line stands for instantaneous process temperature and red line stands for set point which was maintained manually. It must be noted that the actual process temperature follows the set points.

After cryogenic treatment the specimen of HTCST, HTTCST, HTTTCST and HCST are followed by soft tempering. Soft tempering was done in muffle furnace (3.8KW, 230V AC, 600±10°C) at 100°C for one Hr.

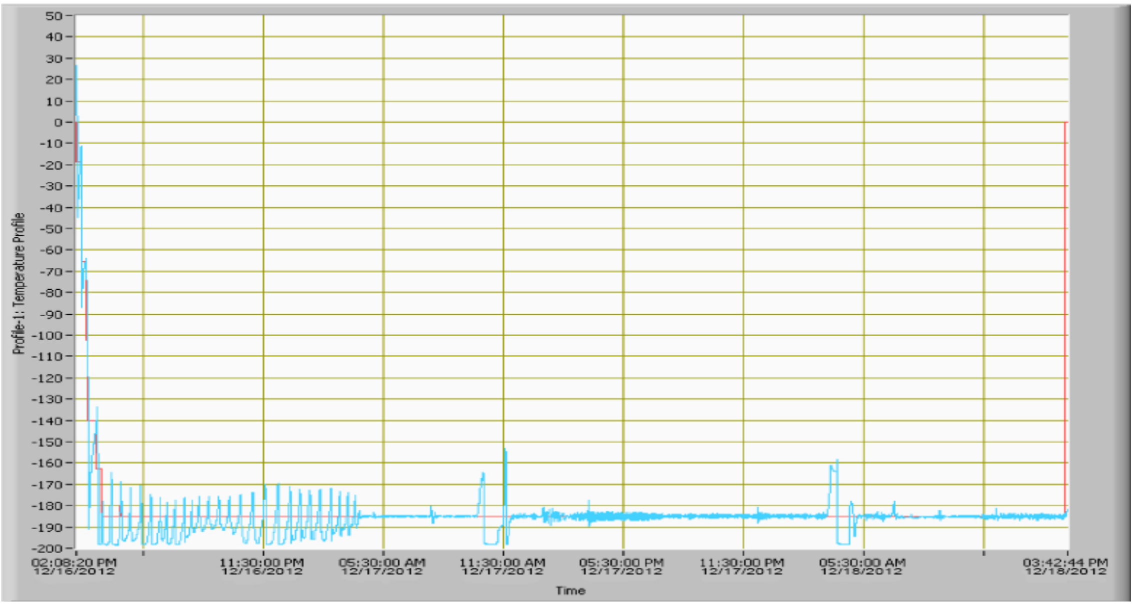
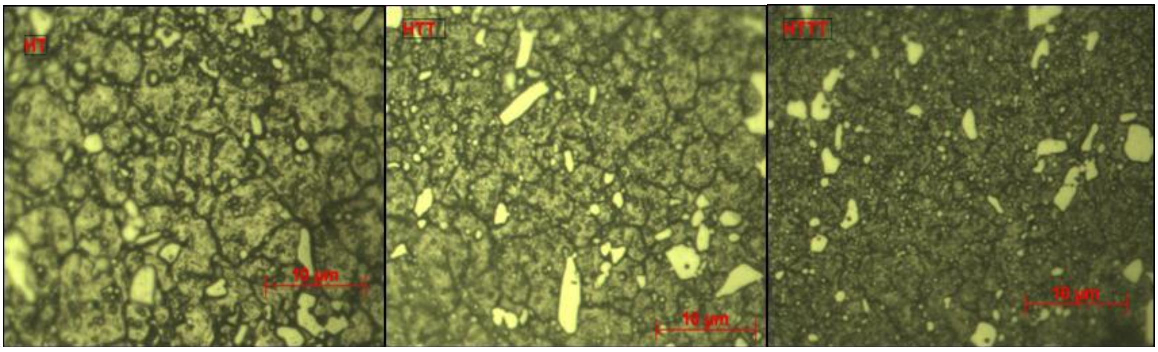


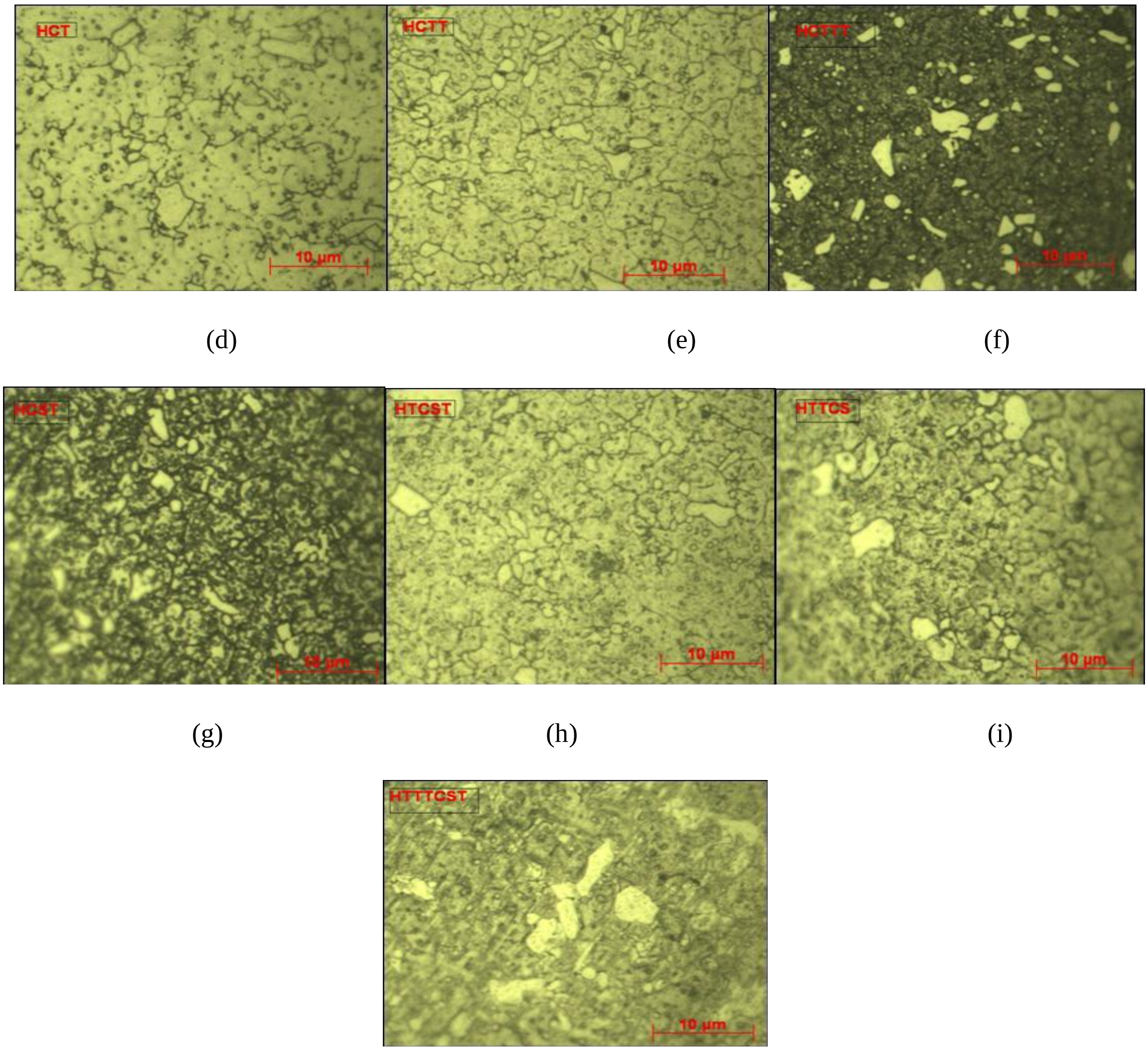
Fig. 3.3 Computer Generated Thermal Profile of Cryoprocessor

c. Metalography

Microstructure analysis was carried by image analyzer software; with inverted microscope (Make-CARL ZEISS Germany, Model-Axiovert 40Mat). Carefully prepared samples were first surface leveled on endless emery belt (80/0) paper. Further samples were subjected to separately polishing on emery paper (240, 400, 600, 800 and 1000) so as to make surface free from scratches. Final polishing was done on velvet cloth polishing machine with intermittent application of fine suspensions of alumina to get better finish on polished surface. A freshly prepared etchant ‘’ Nital’’, of composition approximately 5 ml Nitric acid with 100 ml ethyl alcohol (i.e. approximately 5%), was used for revealing micro constituents of AISI D6 tool steel. Microstructures were then recorded by image analyzer system as shown in Fig. 4.4. Chromium carbides are divided in two categories viz. small size carbides, maximum dimension less than 1 micron, and big carbides, any larger dimension more than 1 micron.



(a) (b) (c)



(d) (e) (f)

(g) (h) (i)

(j)

Fig. 4.4 Microstructure of AISI D6 tool steel for different heat treatments samples at 1000x: a) HT, b) HTT, c) HTTT, d) HCT, e) HCTT, f) HCTTT, g) HC, h) HTC, i) HTTC, j) HTTTC

d. Hardness Measurement

The hardness of polished AISI D6 tool steel specimens was measured on a Rockwell hardness testing machine. The samples prepared for metallography, are used for hardness measurement. The hardness is measured on "C" scale with 10Kg minor load and 150Kg major load applied. A minimum of 5 readings have been taken to estimate the average value of hardness of the specimen. The hardness of different samples is shown in Table no. 4.3.

Table no. 4.3 Hardness of Specimens

Sr. No.	**Sample**	**Hardness (HRC)**	**Hardness (VHN)**
1	HT	59.8	693
2	HTT	60.4	707
3	HTTT	60.6	712
4	HCT	62.8	770
5	HCTT	62.2	753
6	HCTTT	61.4	732
7	HCST	60.1	700
8	HTCST	60.7	715
9	HTTCST	60.3	705
10	HTTTCST	60.1	700

e. Evaluation of Wear Behaviour

In order to investigate the resistance of the heat treated AISI D6 tool steels to adhesion wear; the computerized pin-on-disc tribometer as shown in Fig. 4.5 was used. Dry sliding wear tests were carried out on this computerized pin-on-disc wear testing machine (DUCOM: TR 20LE, India). The specifications of pin-on-disc tribometer are shown in Table no. 4.5. Specimens of 9.20mm diameter and 30mm length was clamped in a holder and held against the rotating counter disc made of WC-coated EN-35 (68 HRC) with the roughness value, Ra = 0.5µm. The faces of the pin specimens were polished and cleaned in acetone in an ultrasonic cleaner. The wear tests were carried out at two different normal loads (F_N) of 30.41N (3.1 Kg) and 50.03N (5.1 Kg) at a constant linear sliding velocity (V) of 1.5m/s and 2.5m/s in dry condition at the room temperature. The values estimated nominal contact pressure in the pin specimens are 0.4575MPa and 0.7526MPa corresponding to F_N of 3.1Kg and 5.1Kg respectively. The wear tests were carried for 60 minutes duration. All these values are shown in Table no. 4.4. The surface of each specimen was cleaned at each time before each test. Every time new track radius of rotating disc was used so that pin was exposed to fresh surface of counter face. Wear and frictional force was measured continuously through a load cell measuring the tangential force.

Fig. 4.5 Experimental Setup of Pin-on-disc Tribometer

Wear rates (W_R) have been estimated by volumetric method from the recorded cumulative height loss of the specimens with respect to sliding distance in the steady-state wear regime considering mean of at least two test results under identical conditions.

Table no. 4.4 Wear Test Details

Sr. No.	Normal Load FN (Kg, N)	Pressure P (MPa)	Velocity V (m/s)
1	3.1,30.41	0.4575MPa	1.5
2	3.1,30.41	0.4575MPa	2.5
3	5.1,50.03	0.7526 MPa	1.5
4	5.1,50.03	0.7526 MPa	2.5

Table no. 4.5 Specifications of pin on disc Tribometer (TR-20)

Make	Ducom Ltd, Bangalore.
Pin Size	3 to 12 mm diagonal
Disc Size	160 mm dia. X 8 mm thick
Wear Track Diameter (Mean)	10 mm to 140 mm
Sliding Speed Range	0.26 m/sec. to 10 m/sec.
Disc Rotation Speed	100-2000 RPM
Normal Load	200 N Maximum
Friction Force	0-200 N, digital readout, recorder output
Wear Measurement Range	4 mm, digital readout, and recorder output
Power	230 V, 15A, 1 Phase, 50 Hz

Table no. 4.6 Rotating Disc Speed in rpm

Sr. No.	Sliding Velocity Disc V(m/s)	Wear Track Diameter D(m)	Disc Speed N(rpm)
1	1.5	0.060	477.5
2		0.080	358.1
3		0.100	286.5
4		0.116	246.9
5	2.5	0.060	795.8
6		0.080	596.8
7		0.100	477.5
8		0.116	411.6

V. RESULTS AND DISCUSSION

a. Microstructure Evaluation

Microstructure of D6 tool steel for HT, HTT, HTTT, HCST, HTCST, HTTCST and HTTTCST specimens exhibit non-uniform distribution of large, elongated, white regions of primary chromium carbides and uniform distribution of nearly spherical secondary chromium carbides. But for HCT, HCTT and HCTTT specimens there is uniform distribution of white regions of primary chromium carbides and nearly spherical secondary chromium carbides. It is clearly seen that there is definite reduction in carbide size as seen in Fig. 5.4 (d) as compared to original structure as seen in Fig. 5.4 (a).

b. Hardness Study

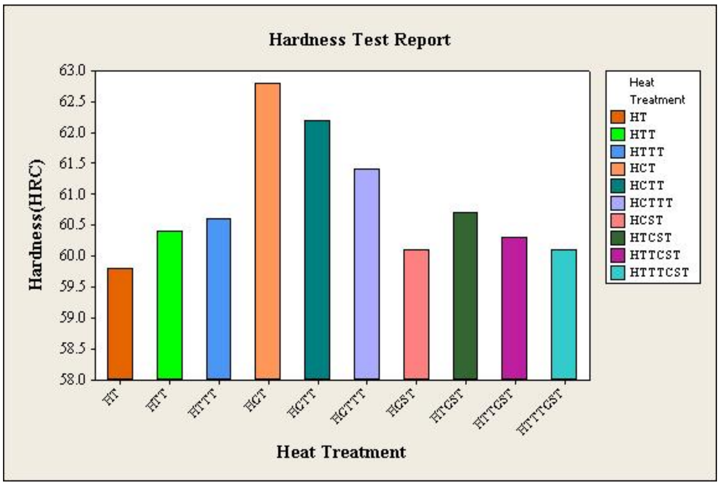


Fig. 5.1 Hardness test report of D6 tool steel for different heat treatment

The measured Rockwell hardness number of D6 tool steel for different heat treatments is tabulated in Table no. 5.3. The results show that the cryogenic treatment increases hardness. From Fig. 5.1, it is observed that for D6 tool steel the hardness of HCT specimens improves approximately 5% as compared to HT specimens. It is also observed that the hardness value for multiple tempering before and after cryotreatment were decreases. The hardness values for specimens subjected to different heat treatment can be directly related to the magnitude of reduction of soft retained austenite with associated improvement in the amount of hard secondary carbides and tough tempered martensite [5]. The obtained results thus infer that increase in hardness of D6 tool steel specimens occurs due to cryotreatment.

c. Wear Mechanism

i. Wear Volume

The wear volumes of the D6 tool steel versus sliding time are presented in Fig. 5.2 - 5.5 for different wear test parameters. It is observed that both normal load and sliding velocity affect the wear volume, which attains values between 1.596 mm^3 to 11.365 mm^3. The wear volume increases with increasing normal load, but wear volume of the D6 tool steel observed to be fluctuating with increase in sliding speed.

It was observed that the cryogenically treated specimens have less wear as compared to conventional heat treatment specimens. Apparently there is no straight correlation with hardness. Even though difference of hardness of HT and HCT specimens is not much more, there is a dramatic drop in wear volume in wear test. There is an increasing wear volume reflected in multiple tempering specimens. From wear test report it is observed that the wear volume was increased in the order of HCT, HCTT, HCTTT, HCST, HTCST, HTTCST, HTTTCST, HTTT, HTT and HT specimens. In the case of HCT Specimens, the large reduction in wear could be mainly due to the retained austenite elimination and the homogenized carbide distribution as well as more chromium carbide as compared to other heat treated specimens.

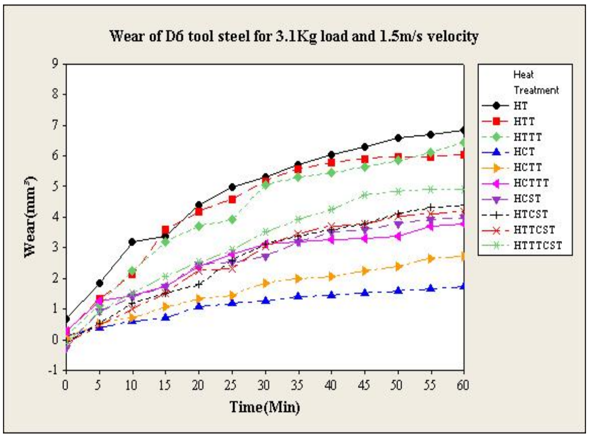


Fig. 5.2 Wear of D6 tool steel for 3.1Kg load and 1.5m/s Velocity for different heat treatment

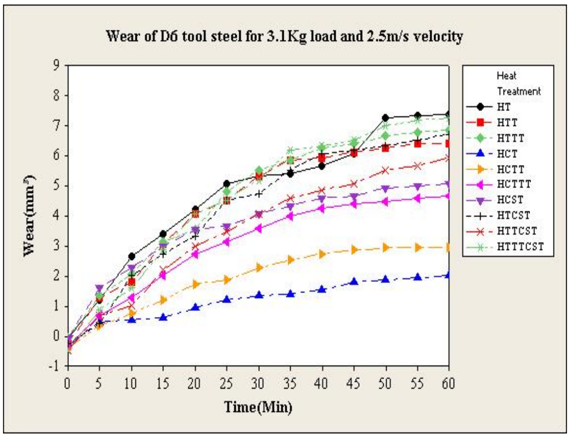


Fig. 5.3 Wear of D6 tool steel for 3.1Kload and 2.5m/s velocity for different heat treatment

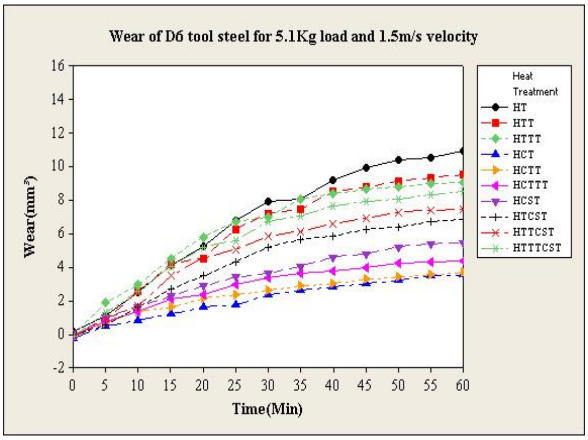


Fig. 5.4 Wear of D6 tool steel for 5.1Kg load and 1.5m/s velocity for different heat treatment

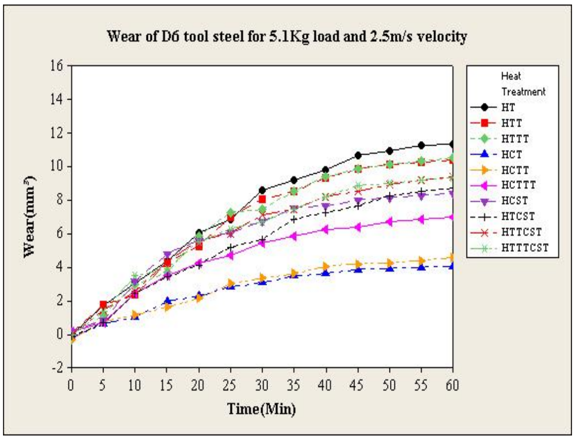


Fig.5.5 Wear of D6 tool steel for 5.1Kg load and 2.5m/s velocity for different heat treatment

5.1. Coefficient Of Friction

The coefficient of friction of D6 tool steel for the different wear conditions for tests carried out and it is observed that, the value of coefficient of friction varies approximately from 0.5324 to 0.7449. The comparison of coefficient of friction between different heat treated specimens is as shown in Fig. 5.6 - 5.9. It is observed that the coefficient of friction decreases with increase in normal load. Wear test report reflect that the coefficient of friction of D6 tool steel increases due to multiple tempering before and after the cryogenic treatment. For HCT specimens the value of coefficient of friction is very less due to largest hardness as compared to other type of specimens. The coefficient of friction of D6 tool steel observed to be fluctuating with increase in sliding speed.

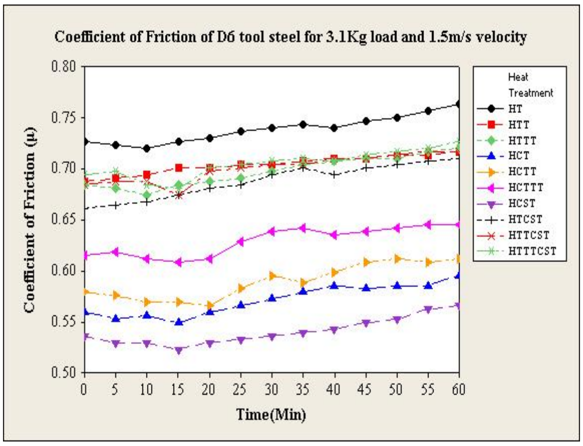


Fig. 5.6 Coefficient of Friction of D6 tool steel for 3.1Kg load and 1.5m/s velocity for different heat treatment

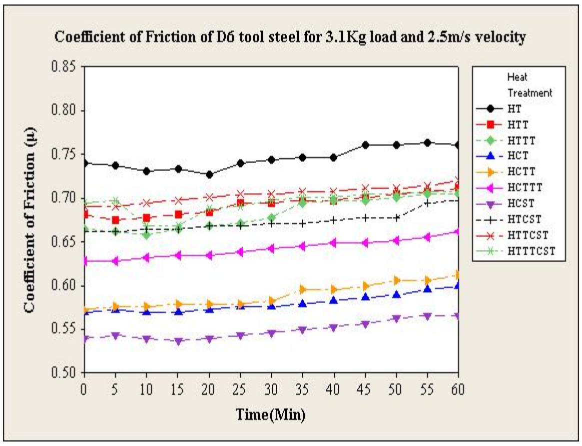


Fig. 5.7 Coefficient of Friction of D6 tool steel for 3.1Kg load and 2.5m/s velocity for different heat treatment

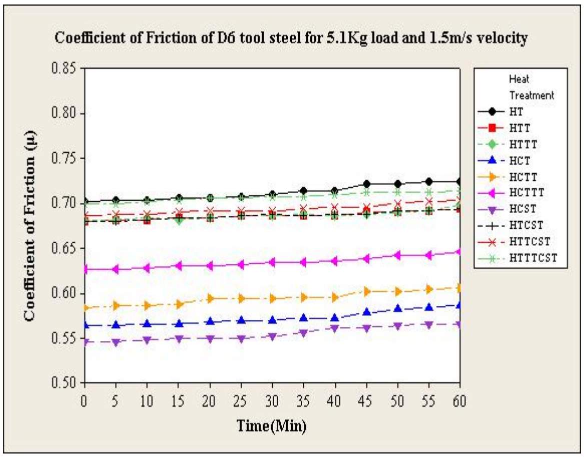


Fig. 5.8 Coefficient of Friction of D6 tool steel for 5.1Kg load and 1.5m/s velocity for different heat treatment

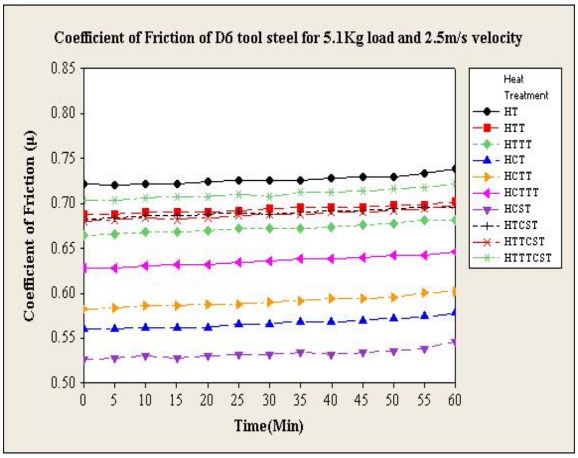


Fig. 5.9 Coefficient of Friction of D6 tool steel for 5.1Kg load and 2.5m/s velocity for different heat treatment

5.2. Wear Rate (W_r)

The computed values of wear rate for all type of D6 tool steel for specimens tested under normal loads 3.1Kg and 5.1Kg are as shown in Fig. 5.10 - 5.13. It is observed that both normal load and sliding velocity affect the wear rate, which attains values between 0.2955 mm^3/m to 1.9942 mm^3/m. The results in these figures show that the wear rate of HCT specimens is very less as compared to other type of heat treated samples and where as there is an increasing wear rate reflected in double and triple tempered D6 tool steel. In the case of HCT specimens, the large reduction in wear rate could be mainly due to the homogenized carbide distribution, additional amount of fine carbides nucleated during cryogenic treatment and reduction in carbide size as compared to other heat treated specimen's i.e.

Wear behavior is highly influenced by microstructural parameter like carbide size and its distribution. It is also observed that the wear rate increase linearly with increasing normal load for all types of specimens. High wear rate in case of HT, HTT, HTTT, HCTT, HCTTT, HCST, HTCST, HTTCST, and HTTTCST specimens as compared to HCT specimens could be attributed to primary coarse carbides. The lowest wear rate is shown by HCT specimens as a result of additional amount of the fine carbides nucleated during cryogenic treatment.

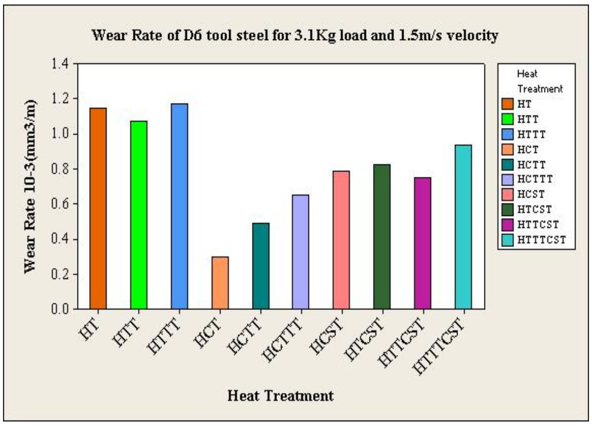


Fig. 5.10 Wear Rate of D6 tool steel for 3.1Kg load and 1.5m/s velocity for different heat treatment

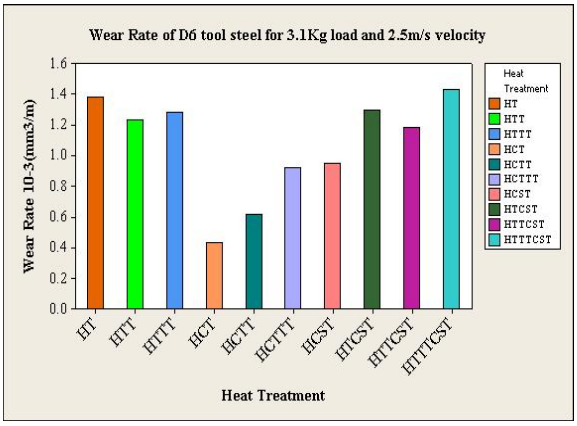


Fig. 5.11 Wear Rate of D6 tool steel for 3.1Kg and 2.5m/s velocity for different heat treatment

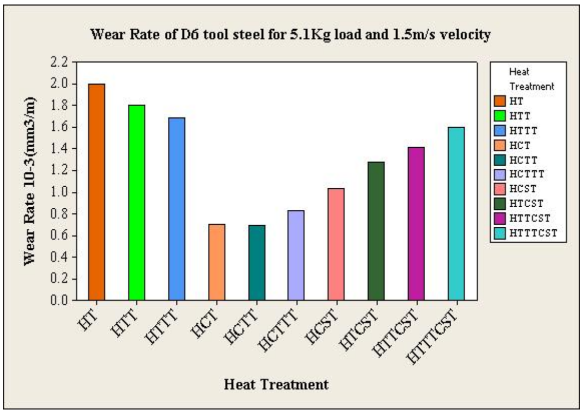


Fig. 5.12 Wear Rate of D6 tool steel for 5.1Kg load and 1.5m/s velocity for different heat treatment

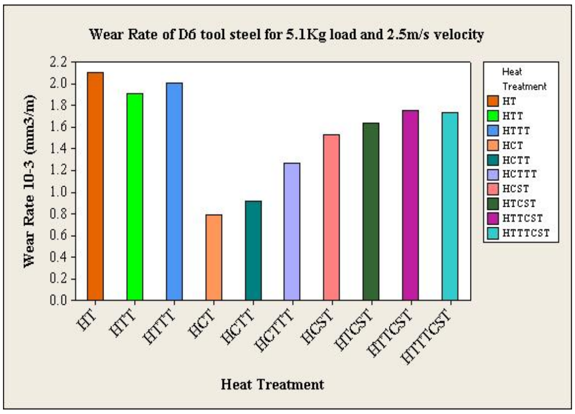


Fig. 5.13 Wear Rate of D6 tool steel for 5.1Kg load and 2.5m/s velocity for different heat treatment

5.3.Wear Resistance (Wr)

Wear behavior can be conveniently expressed in terms of dimensionless wear coefficient (k). The inverse of dimensionless wear coefficient is known as wear resistance (WR). The calculated wear resistance of different heat treated specimens are as shown in Fig. 5.14 - 5.17. The results obtained in this study, in general, are in agreement with results reported by Dass et al [5]. In this study it is observed that the improvement in wear resistance is significant by cryogenic treatment.

5.4.Improvement in wear resistance (α %)

In order to quantify the magnitude of improvement of WR by HCT over that of HT treatment specimens, a parameter has been considered here, which is defined as follows,

$$\alpha\ \% = [\frac{WR_{HCT}}{WR_{HT}}] \times 100$$

Where, WR is wear resistance, HCT and HT denote the type of the specimen [5, 7].The value of have been calculated for different types of specimens under different test conditions. As compared to other type of samples, there is greatest improvement in wear resistance in case of HCT samples. The results shown that for 3.1 kg and 5.1Kg normal load, at 1.5m/s and at 2.5m/s velocity, which illustrates that in comparison to HT, HCT treatment enhance the WR of D6 tool steel by 140.501% to 248.559%. In addition, the magnitude of for HT and HCT specimens decreases with the increasing normal load and velocity.

The relation between wear properties with the results of microstructure analysis revels that the improvement in wear resistance is depends on the microstructure analysis generated by different heat treatments irrespective of its dependence on wear test conditions. It can be concluded at this stage that the reduction of retained austenite content, reduction in size of the secondary carbide and distribution of secondary carbides are basic factors responsible for the improvement in wear resistance in HCT specimens; whereas wear resistance property deteriorates with double and triple tempering as evident from Fig. 5.14 - 5.17. In the HT,

HTT, HTTT, HCTT, HCTTT, HCST, HTCST, HTTCST, and HTTTCST of D6 tool steel specimens there is growth in secondary carbide size. This contributes in deteriorating the wear resistance of D6 tool steel.
This experimental work shows that the combined effect of heat treatment and cryogenic treatment can assist in improving wear resistance in single tempering, whereas wear resistance deteriorate in subsequent double and triple tempering.

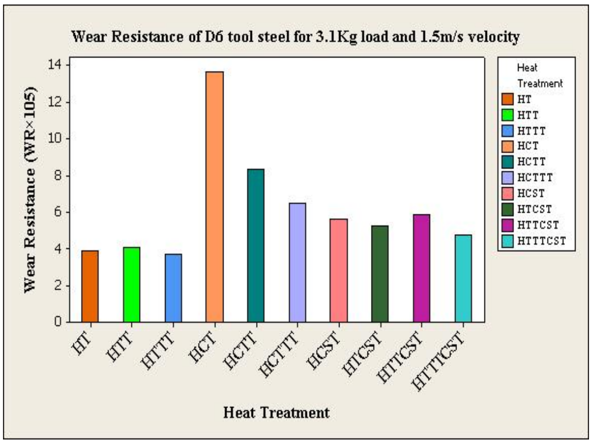


Fig. 5.14 Wear Resistance of D6 tool steel for 3.1Kg load and 1.5m/s velocity for different heat treatment

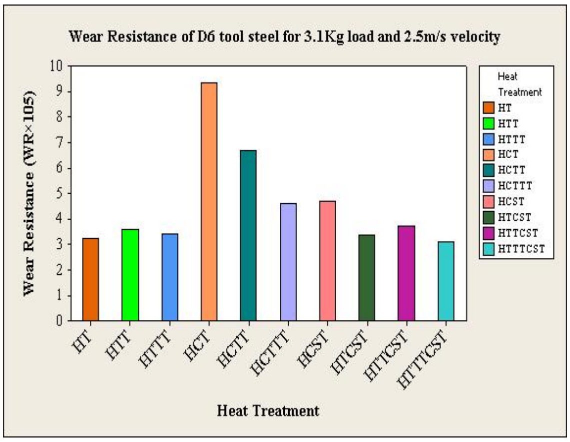


Fig. 5.15 Wear Resistance of D6 tool steel for 3.1Kg load and 2.5m/s velocity for different heat treatment

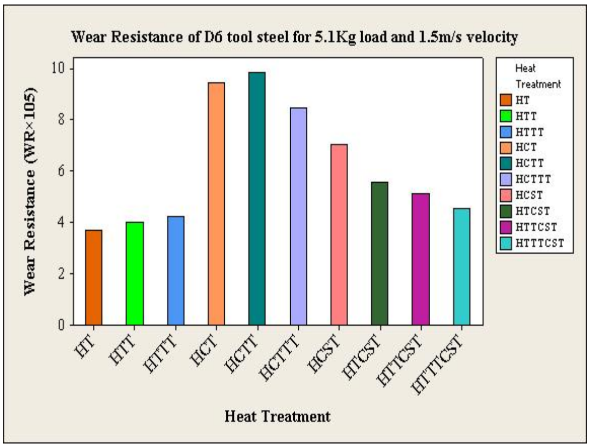


Fig. 5.16 Wear Resistance of D6 tool steel for 5.1Kg load and and 1.5m/s velocity for different heat treatment

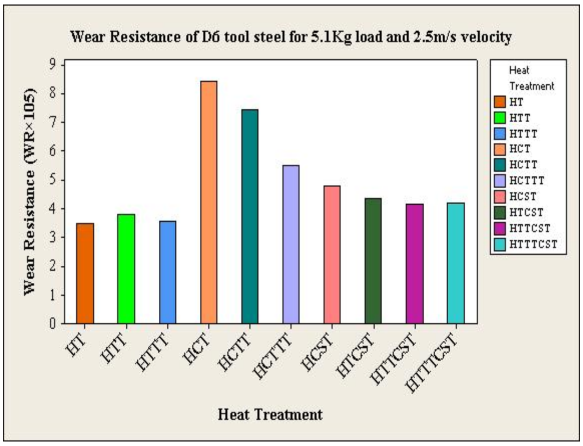


Fig. 5.17 Wear Resistance of D6 tool steel for 5.1Kg load 2.5m/s velocity for different heat treatment

d. Statistical Regression Analysis

Statistical regression analysis is the study of the relationship between two or more variables, used to establish the empirical equation relating input-output parameters, by utilizing least square method. Moreover, it is the most commonly used statistical modeling technique developed based on experimental data. There is difference between predicated and actual values of the response for the same set of independent variables. It is possible to attribute this difference to a set of independent variable and the difference due to random or experimental errors. The technique of analysis of variance (ANOVA) does this. With the help of regression coefficients we can calculate the correlation coefficients. The square of coefficients, called coefficients of determination R^2(R-Sq), measures the degree of association of correlation that exists between the variables. The value of R^2(R-Sq) is the important criteria to decide the validity of regression model. In general, greater the value of R^2(R-Sq) better is the fit and more useful the regression equation is as predictive device. If value is 0.85(85%) or more, then relationship established by regression model is acceptable.

5.5. Regression Analysis for D6 Tool Steel Specimens

The regression analysis was done on Minitab 16 Software for Wear Rate versus Load, Speed and following regression equations has been developed to predict the wear rate for HCT specimen.

Regression Analysis: Wear Rate versus Load, Speed

The regression equation is

```
Wear Rate = - 0.000449 + 0.000191 Load + 0.000111 Speed

Predictor          Coef     SE Coef       T      P
Constant    -0.00044934  0.00007108  -6.32  0.100
Load         0.00019063  0.00001222  15.59  0.041
Speed        0.00011075  0.00002445   4.53  0.138

S = 0.00002445   R-Sq = 99.9%   R-Sq(adj) = 99.6%

Analysis of Variance

Source          DF           SS           MS       F      P
Regression       2  1.57617E-07  7.88086E-08  131.83  0.061
Residual Error   1  5.97802E-10  5.97802E-10
Total            3  1.58215E-07

Source  DF       Seq SS
Load     1  1.45352E-07
Speed    1  1.22656E-08
```

It was observed that the regression analysis carried out shows that, the value of R^2(R-Sq) for HCT specimen has greater the value **99.6%,** thus better is the fit and more useful the regression equation is as predictive device.

VI. CONCLUSION

The present investigation is based on the effect of cryogenic treatment on friction and wear behaviour of AISI D6 tool steel. After conducting the experimental work, following conclusions are drawn from the results.

1) The wear volume and wear rate (W_R) increases linearly with increasing normal load for all type of samples, whereas coefficient of friction decreases with increase in normal load.
2) It is observed that at higher velocities, wear rate is enhanced, but the coefficient of friction observed to be fluctuating.
3) It is seen that the largest improvement in wear resistance (WR) is observed in HCT specimens, which is 140% to 248% that of the HT specimens. Subsequent tempering, i.e. double and triple tempering deteriorates wear resistance. The improvement in WR decreases with increasing severity of wear test conditions, i.e. increasing normal load.
4) Wear volume, coefficient of friction, wear rate and wear resistance of the materials depends upon the combination of heat treatments.
5) The Rockwell hardness number of HCT specimens improves approximately 5% by HT specimens. Cryogenically treated specimen shows decreasing hardness from single stage to triple stage tempering.
6) Therefore, among different heat treatments like HT, HTT, HTTT, HCT, HCTT, HCTTT, HCST, HTCST, HTTCST and HTTTCST; the lowest wear volume, coefficient of friction and wear rate is observed in HCT specimens.

As a result of the lower retained austenite, the cryogenic treatment improves the wear resistance and the hardness of the D6 tool steel. This improvement is significant in the deep cryogenic treatment due to more homogenized carbide distribution, the retained austenite elimination and higher chromium carbide percentage in comparison with the conventional heat treatments.

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