Effect of Deep Cryogenic treatment on AISI A8 Tool steel & Development of Wear Mechanism maps using Fuzzy Clustering

Nandakumar Pillai ¹, Dr. R Karthikeyan ²,
Department of Mechanical Engineering, BITS Pilani, Dubai Campus, UAE

Abstract: Tool steels are widely classified according to their constituents and type of thermal treatments carried out to obtain its properties. Viking a special purpose tool steel coming under AISI A8 cold working steel classification is widely used for heavy duty blanking and forming operations. The optimum combination of wear resistance and toughness as well as ease of machinability in pre-treated condition makes this material accepted in heavy cutting and non cutting tool manufacture. Air or vacuum hardening is recommended as the normal treatment procedure to obtain the desired mechanical and tribological properties for steels under this category.

In this study, we are incorporating a deep cryogenic phase within the conventional treatment cycle both before and after tempering. The thermal treatments at sub zero temperatures up to -195°C using cryogenic chamber with liquid nitrogen as medium was conducted. Micro structural changes in its microstructure and the corresponding improvement in the tribological and physical properties are analyzed. The cryogenic treatment leads to more conversion of retained austenite to martensite and also formation of fine secondary carbides. The microstructure is studied using the micrographs taken using optical microscopy.

The wear tests are conducted on DUCOM tribometer for different combinations of speed and load under normal temperature. The wear rates and coefficient of friction obtained from these experiments are used to developed wear mechanism maps with the help of fuzzy c means clustering and probabilistic neural network models. Fuzzy C means clustering is an effective algorithm to group data of similar patterns. The wear mechanisms obtained from the computationally developed maps are then compared with the SEM photographs taken and the improvement in properties due to this additional cryogenic treatment is validated.

Key words: - Cold working tool steel, Deep cryogenic treatment, Fuzzy C means clustering, Wear mechanism maps
1. Introduction:
The material selected for the study is Viking tool steel which is a commercial grade tool steel with high chromium content classified under AISI A8 series of tool steels. Tool steels in general exhibits excellent post thermal treatment mechanical and tribological properties. The presence of carbon and other alloying constituents determine the characteristics of the steel as the formation of carbides and corresponding phase changes attributes to the surface properties of the steel [1]. The table1 below shows the chemical composition of VIKING tool steel. Among the metallic alloying content chromium is rich and hence it is classified as high chromium cold working tool steel.

Table 1 Chemical composition of Viking tool steel

| Element | C  | Si  | Mn  | Cr  | Mo  | V  |
|---------|----|-----|-----|-----|-----|----|
| (%)     | 0.5| 1.0 | 0.5 | 8.0 | 1.5 | 0.5|

2. Experiment:
The stock of 32mm diameter round bar is used for making the specimen of 15mm diameter and 100 mm long. It is then heat treated at an austenizing temperature of 1050°C for 30 minutes time. The temperature has been raised to this level in gradual steps. The specimens are then allowed to cool to the room temperature with forced air circulation. At this stage, the steel has a microstructure consisting of martensite, retained austenite and carbides [2].

The material is then treated cryogenically at a temperature of -190°C in the cryogenic chamber for duration of 4 hours. Liquid nitrogen is used as the cryogenic medium to obtain this sub zero temperature. The fig 1 shows the cryogenic arrangement made for conducting this experiment.

![Cryogenic experimental set up used](image)

The hardened specimen is transferred to the cryogenic chamber and liquid nitrogen is connected to the chamber to obtain the desired temperature of -190°C. The specimen is kept at this stabilized temperature for 4 hours and then brought back to room temperature. Cryogenic treatment is added to the conventional
treatment as an intermediate process between hardening and tempering [3]. The specimen is then subjected to tempering and is done twice at 400°C as the final process of thermal treatment cycle.

The wear tests are conducted on DuCOM pin on disc wear tester for the deep cryogenically treated (DCT) specimen, as per ASTM G99-05(2016), to study the tribological behavior. The DCT sample is used as the pin and is tested against a standard hardened disc of 65 HRC of 100mm diameter. The speed selected varied from 400 to 600 rpm with wear track diameter of 60mm and 50 mm. The load applied is in the range of 1 kg to 4 kg and tests are conducted for various combinations of these parameters. Load cell and displacement transducer are used to measure the friction force and wear rate. The results obtained are for the combination of five different sliding velocities with five different loads. The data obtained in each combination is tabulated.

![Figure 2 Dry test on Pin on Disc Wear Tester](image)

The wear tester will give the direct values of frictional force, coefficient of friction and wear rate. The tests are conducted at ambient conditions without using any kind of lubricants. The graphs obtained from the tests conducted at various combinations of speeds and loads are plotted. With these data the sliding velocity in m/s and wear rate in microns per meter is calculated and these values are used to generate the COF and wear rate graph with the help of clustering analysis.

2.1 Development of Wear mechanism maps:

Wear mechanism maps are used to depict the types of wear caused in a particular tribo system. Any two or more moving parts form a tribo system. The wear occurring depends upon the surface properties of the material mating, ambient condition at which movement take place, type of lubrication adopted etc. The sliding velocity between the components and the normal forces are the major factors that determine the type and severity of the wear. Wear mechanism map is one which shows various kinds of wears in a system and the conditions at which particular one prevail. The flow chart given in figure 3 shows the steps involved in developing wear mechanism maps with the help of Fuzzy C means clustering (FCM).
Fuzzy c-means (FCM) clustering is an unsupervised method derived from fuzzy logic that is suitable for solving multiclass and ambiguous clustering problems [4]. In FCM clustering method same data may belong to more than one cluster and basically used for pattern recognition. The similarity is based on membership values ranging from 0 to 1 and each data sample is assigned with a membership value considering its similarity with the centre of the cluster.

The objective function used for minimization is

\[ J_m = \sum_{i=0}^{N} \sum_{j=1}^{C} u_{ij}^m \|x_i - c_j\|^2 \quad 1 \leq m \leq \infty \]

where \( m \) is any real number greater than 1, \( u_{ij} \) is the degree of membership of \( x_i \) in the cluster \( j \), \( x_i \) is the \( i \) th of \( d \)-dimensional measured data, \( c_j \) is the \( d \)-dimension center of the cluster, and \( \| \cdot \| \) is any norm expressing the similarity between any measured data and the center. Based on the applied load the normal force is known and is expressed in Newtons (N) and the sliding velocity (m/s) can be obtained.
from the speed in rpm and the wear track diameter in mm. The tests are conducted for different combinations of speed and load and the data are tabulated to generate the coefficient of friction (COF) and wear rate graphs. COF is the ratio of the frictional force to the normal force and increase in frictional force will increase the COF and more friction can lead to more wear. Wear rates are measured linearly in microns per unit meter.

3. Results and Discussion:

![Figure 4. Wear rate map with Sliding velocity vs Normal force](image1)

![Figure 5. Coefficient of friction map with Sliding velocity vs Normal force](image2)
The stress due to load and heat from the friction are the main reasons for the development of wear at their contact surface and the magnitude of these forces will play the major role to determine the wear rates [5]. The wear rates graph given above in fig 4 is plotted with sliding velocity along x axis and normal force along y axis. The wear rate is high in the region with high loads and sliding speeds and is very less when the speed and load is low. The maximum value of wear rates is in the range of 0.14 to 0.16 microns and is observed in the region with high normal force and sliding velocity. The wear rates are very less in the low speed, low load region.

The coefficient of friction (COF) graph for DCT specimen, shown in fig 5, is also generated with sliding speed and normal force. COF or frictional force is more when the load is high and is increasing as the sliding velocity increases. COF is directly related to load but may or may not depend on speed [6]. The COF values are maximum and is nearing almost 0.55 when the load is high and for the velocity range of medium to high. COF is more dependent on the load than sliding velocity. Though other parameters can also influence the values of COF it is primarily related to the applied load.

The COF data and the wear rate data are clustered with the help of FCM for the same range of sliding velocity and normal force. The data with the similarities are clustered together indicating wear of similar nature. Fig 6 is the wear mechanism maps obtained with the help of FCM clustering and maps are plotted with sliding velocity on x-axis and normal force on y-axis.

Figure 6. Wear mechanism map of DCT specimen.
The types of wears are adhesive wear, abrasive wear, oxidative wear and combination of these wears. When the sliding velocity and the load are high the predicted wear is more abrasive in nature while in the slower speed range the wear occurring is of adhesive in nature. As the load applied on the pin increases the frictional force will be more and scratches may form on the pin material as the standard disc used for the test is harder than the pin. During abrasion the scratches or lines will appear on the softer material of the two mating components. Oxidative wear is also seen on the surfaces as the tests are done in dry conditions and oxidative wear will be more when the velocity is high due to high temperature at these conditions [7-8].

![Figure 7. Microstructure of DCT specimen showing the presence of carbides and martensitic lath structure.](image)

With deep cryogenic treatment the surface hardness is more due to more precipitation of primary and secondary metallic carbides. Another contributing factor for the hardness is the conversion of retained austenite to martensite and the analysis of the microstructure reveals clear martensitic lattices. The material hardness is in the range of 63 HRC which is higher than the conventionally treated specimen and correspondingly the wear properties are also better in comparison. The SEM photos taken for the microstructure of the DCT treated specimen given in figure 7 is showing the presence of metallic carbides formed during the treatment and the formation of martensitic lath structure.

The SEM analysis of the worn surfaces of the specimen is also taken to study the nature of wear occurred on the mating surface of the material. The SEM results as shown in figure 8 also indicate three types of wears such as abrasive, adhesive and oxidative wear and combination of these wears. However with the inclusion of cryogenic treatment in between the conventional cycle the hardness of the surface has been improved which lead to a reduction in wear rate and coefficient of friction.
Figure 8. SEM photographs of worn out surfaces of DCT specimens showing types of wear.

4. Conclusion

The Fuzzy C means clustering is an effective tool for developing wear mechanism maps. The predicted wear from the wear mechanism map developed with this technique is almost justifying the results obtained from the SEM photos. This confirms the suitability of this technique for such kind of applications with pattern recognition. The improvement in the tribological behavior for the DCT specimen is clear as the surface hardness has been increased by around 3-5 HRC, while the wear rate and COF has reduced by 15 % when compared with the untreated specimen. Deep cryogenic treatment can be used as a secondary treatment process to improve the wear properties of VIKING tool steel considering the tooling type and criticality of the production in comparison to the cost effectiveness.

5. References

[1] Wale A D and Wakchaure V D, Effect of Cryogenic Treatment on Mechanical Properties of Cold Work Tool Steels 2013 International Journal of Modern Engineering Research Vol.3, Issue.1, pp-149-154

[2] Chiu L, Liao H, Lin C, Pan Y, Lion H 2012 Carbide Distribution Effect on Wear Behavior of Cold work tool steels; Advanced Material research

[3] Das D, Dutta A K., Ray K.K 2009 Influence of varied cryo treatment on the wear behavior of AISI D2 steel, Wear 266 pp297–309
[4] Alata M, Molhim M and Ramini A 2013 Using GA for Optimization of the Fuzzy C-Means Clustering Algorithm, Research Journal of Applied Sciences, Engineering and Technology 5(3): pp695-701.

[5] Okonkwoa P C, Kellya Georgina, Rolfe B F, Pereiraa M P 2012 The effect of temperature on sliding wear of steel-tool steel pairs; Wear pp282–283 22–30

[6] Ameen H A, Hassam K S, Mubarak E M M 2011 Effect of loads, sliding speeds and times on the wear rate for different materials American journal of scientific and industrial research.

[7] Akhbarizadeh A, Shafyei A, Golozar M A 2009 Effects of cryogenic treatment on wear behavior of D6 tool steel Materials and Design 30(8):pp3259-3264.

[8] Naravade R H, Belkar S B, Kharde R R 2013 Effects of Cryogenic Treatment, Hardening and Multiple Tempering On Wear Behavior of D6 Tool Steel The International Journal Of Engineering And Science 2/5 (2013) 1-15.