Optimization of Heat Treatments for Wear Analysis of D5 Tool Steel by Using DOE/RSM

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Abstract:- This work to be investigating role of multiple heat treatment on friction and wear behaviour of D5 tool steel classified by American Iron and Steel Institute (AISI).The aim of the present work was to investigate the effect of different heat treatment parameters. Selection of the proper austenizing temperature is also an important factor, with higher austenizing temperature resulting in higher friction and wear. The effect of different combination heat treatment like hardening within range of 996°C-1010°C for 1 hour, tempering within range of 177°C-316°C for 2 hours, Cryogenic treatment at -185°C for within range of 20 to 40 hours .Efforts would have to be performing test for different velocity and load using pin-on-disc instrument. The combination of heat treatment would have to be optimised. For that purpose Design of Experiment (DOE) is performed. The DOE is done with help of statistical tool i.e. minitab 16 . Produced optimum runs with help of Response surface methodology (RSM) by Box-Behnken design.

Keywords:- AISI D5 tool steel, cryogenic treatment (CT), wear behaviour, Design of Experiment (DOE), Response Surface Methodology (RSM), retained austenite (_R)

I.   INTRODUCTION

In metal forming industry tools can be exposed to very complex and surface demanding conditions, which are the result of different effects (mechanical, thermal, chemical or tribological loading) and require well defined mechanical and especially tribological properties. Wear which is one of the main cause of material wastage, is an important problem associated with industrial components. Though wear resistance is not a materials property, an understanding of the dominant wear mechanisms is very essential. The cost of wear to industry is high and the recognition of this fact lies behind the continuing development in the field of advanced materials, in order to provide a solution for mitigating tribological losses. (1)

The wear rates at different loads and sliding velocities, morphologies of the worn-out surfaces and the characteristics of the wear debris have been systematically examined to assess the possible critical duration of cryotreatment to achieve the best wear resistance property. The wear experiments have been supplemented by detailed microstructural investigations with an emphasis to reveal the amount of retained austenite and the characteristics of the secondary carbide particles apart from hardness evaluation. (2)

Cryogenic treatment is not, as often mistaken for, a substitute for good heat treatment, but is a supplemental process to conventional heat treatment before tempering. It not only gives dimensional stability to the material, but also improves abrasive and fatigue wear resistance,
and increases strength and hardness of the material The main reason for this improvement in properties are the complete transformation of retained austenite into martensite and the precipitation of fine carbides into the tempered martensitic matrix. (1)

Bourithis et.al(3) studied commercial cold work tool steels, AISI D2 and O1. These tool steels were heat treated in order to obtain the same hardness 700 VHN (60 HRC) and were subsequently tested in three different modes of wear, namely in adhesion, three-body and two-body abrasion, by using pin-on-disk, dry sand/rubber wheel apparatus and pin abrasion on SiC, respectively.

Their results show that for relatively low sliding speeds, AISI O1 steel performs up to 12 times better than AISI D2 steel in adhesive wear. For higher sliding speeds, however, this order is reversed due to oxidation taking place on the surface of the AISI D2 steel. The friction coefficient of the AISI O1 tool steel against Al_2O_3 is constant regardless of the conditions applied and has a value of 0.55. The friction coefficient of AISI D2 tool steel against Al_2O_3 decreases progressively from 0.74 to 0.58 with increasing sliding speed, due to a change in the primary wear mechanism from delimitation to oxidation wear.

Akhbarizadeh et.al(4) 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.

Amini et.al(5) studied the effect of cryogenic treatments on the wear behavior of 80CrMo12 5 tool steel was studied using two different temperatures: -80 C as the shallow cryogenic temperature and -196 C as the deep cryogenic temperature. The cryogenic treatments increase the wear resistance and harnesses. Shallow cryogenic treatment (SCT) decreased the retained austenite by 6% for the SCT24 sample. In deep cryogenic treatment (DCT), as well as the retained The hardness and wear resistance of the DCT samples depend on the holding time, showing a maximum at 48 h holding time. The decrease beyond 48 h was attributed to the decrease in the carbides homogeneous distribution.

II. EXPERIMENTAL DETAILS

A. Material for Disc

The disc of diameter 160mm and thickness 8 mm is selected as the rotating counter surface. The tungsten carbide coated EN 31 steel is to be select. The disc having four equidistance holes at 145 mm pitch circle diameter as fig.2.1.
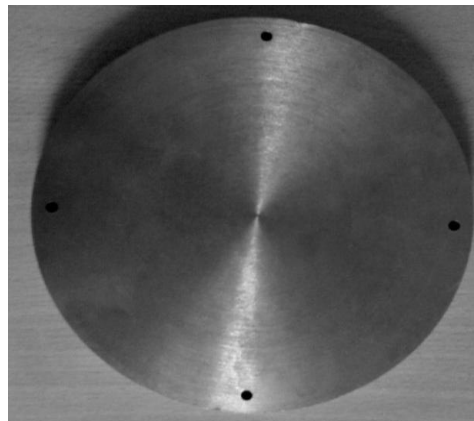

Fig.2.1. Disc

B. Material for Pin

The investigation has to be conduct with samples of AISI D5 tool steel. AISI D5 tool steel is also designated as T30405 by Unified Numbering System. The round bars of diameter range 3-12 to be select for this experimentation as shown in fig 2.2. The specimens for wear test were prepared of diameter 3-12mm and height 30mm. For hardness test specimens were prepared of diameter 10mm and height 10mm. The chemical composition of specimen (diameter 8mm; height 15mm) as analyzed by vacuum spectrometer is given in Table.2.1 .

Table 2.1. AISI D5 steel chemical composition

C	Si	Mn	P	S	Cr	Ni
$\leq$	$\leq$	$\leq$	$\leq$	$\leq$		
1.4-1.6	0.1-0.6	0.2-0.6	0.03	0.03	11-13	
Mo	Al	Cu	Nb	Ti	V	Ce
0.7-1.2					$\leq$ 1.0	
N	Co	Pb	B	Other		
	2.5-3.5					

C. Principle alloying element in Pin

Principle allowing elements and their effect on material properties are summarized as below:

- Carbon (C)
  Carbon is by far the most important alloying element for the hardening properties of all steel types, including tool steels.

- Chromium (Cr)
  Chromium forms carbides and increases hardness, wear resistance, corrosion resistance and tempering resistance.
- Molybdenum (Mo)
  Tungsten and molybdenum exhibit similar effects. Addition of both elements results in grain refinement.
- Vanadium (V)

Originally vanadium was used as a scavenger to remove slag, impurities, and to reduce nitrogen dissolved in the matrix and to act as de-oxidant during the production of the steel. It is found that vanadium formed very hard and thermally stable carbides usually as isolated particles. These carbides improve the resistance against abrasive wear and provide very good cutting performance.

- Manganese (Mn)
  It increases the depth of hardening; Manganese containing steels can be hardened in oil, even though manganese augments the retained austenite content.
- Silicon (Si)
  In general silicon improves resistance against softening of martensite, and displaces tempered martensite embrittlement to higher temperatures.
- Cobalt (Co)

Cobalt is a hard ferromagnetic, silver-white, hard, lustrous, brittle element. Addition of nickel increases the strength of the steel by entering into solid solution in ferrite. It is used in low alloy steels to increase toughness and harden ability. Presence of nickel reduces lattice distortion and cracking during quenching.
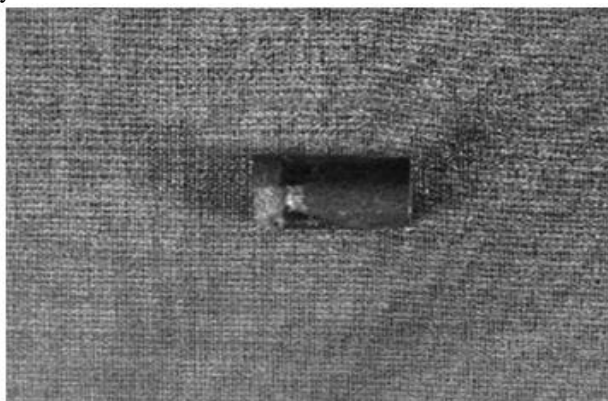

Fig.2.2. pin.

D.   Treatments

The material selected for this work was given various treatments and treatment combinations.

- Hardening
  The first step in the heat treatment of AISI D5 tool steel was hardening. The purpose of hardening to harden steel to increase the wear resistance, cutting ability. Hardening of AISI D5 tool steel was done in the tubular furnace (3.5KW, 230V AC, 15A, 1200±10°C) at a temperature of 996-1010°C for 1 Hour. During hardening process, inert gas Argon to be supply in tubular furnace to avoid oxidation. Harden AISI D5 tool steel follow air cooling which provides great benefit of minimizing distortion and dimensional changes.
- Tempering
  The process which consists of heating the hardened components to a temperature between 100°C ato700°C, holding at this temperature for specific period and cooling to room temperature, usually by air is called as "tempering". For D5 tool steel tempering within range of 177°C-316°C for 2 hours.

Purpose of tempering is as follows

1. 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,
2. To reduce hardness and to increase ductility and toughness,
3. To eliminate retained austenite (_R)[12].

- Cryogenic treatment
  The subzero treatment means the treatment carried out below 0°C for predetermined soaking time. As per the level of temperature chosen below subzero and prevailing understanding about the subzero treatments, the following classification/definition is proposed

1. Shallow Subzero Treatment (ST) is meant for temperature regime from 0°C to -80°C.
2. Deep Subzero Treatment (DT) is meant for temperature regime from -80°C to -150°C.

3. Cryogenic Subzero Treatment (CT) is meant for temperature regime below -150°C. [3]

Table.2.2. Specification of Tribometer (TR-20)

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

Cry Processor is capable of maintaining shallow sub zero treatment, deep sub zero treatment and cryogenic sub zero 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. To understand the effects of cryogenic processing it is essential that one 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. The Fig shows cryogenic cycle as given.
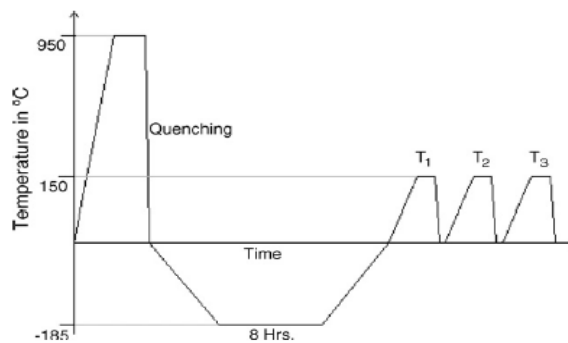

Fig.2.3. Processing routes of the cryogenic treatment

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 (4).
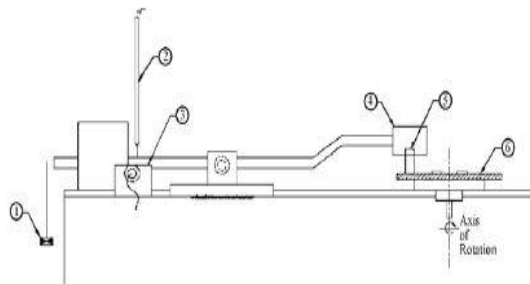
E. Evaluation of wear behavior

Fig. 2.4 . Schematic of pin-on-disc wear testing machine

(1) load; (2) Y-recorder; (3) load cell; (4) specimen holder (collet); (5) specimen; (6) counter face disc.

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. 2.2. Specimens of 10mm diameter and 30mm length clamp in a holder and held against the rotating counter disc made of WC-coated EN-31 (68 HRC).The faces of the pin specimens to be polish and clean in acetone in an ultrasonic cleaner.(7)

During testing, pin of D-5 steel specimen to be keep stationary while the circular disc rotates. The test sample was clamped in a holder and held against the rotating steel disc as shown in fig. 2.4. schematically. The wear rate is reported as an average of wear rates of three samples. (8)
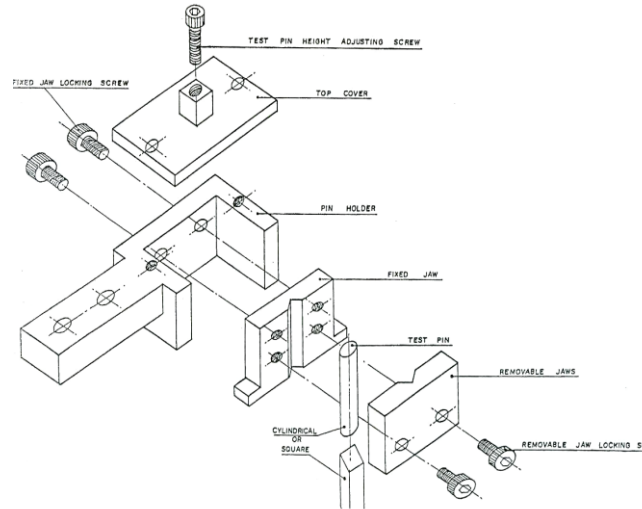

Fig.2.5 .Exploded View of Pin Holder

F.   Hardness measurement

For hardness measurement, Rockwell hardness tester to be use. For D-5 steel material HRC scale was used. Minor loads first apply to seat the specimen. The major load then applies for HRC scale for duration of 30 s. The depth of resistance to indentation was automatically recorded on the dial gauge.(9)

G.   Cryogenic equipment

Fig.2.6. is a schematic representation of cryogenic equipment. It comprises an insulated box (cryo box), One motor with circulating fan, one thermocouple to measure the cryogenic temperature inside the box connected to a temperature controller and programmer, a liquid nitrogen tank and solenoid valve for gas inlet.(10)
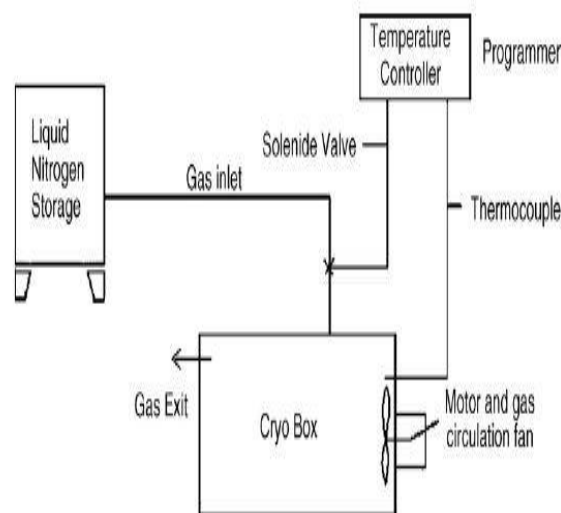

Fig.2.6.Block diagram explaining operating principle of the cryogenic equipment.

III.   SYSTEM DEVELOPMENT

A.   Design of Experiment

It is methodology based on statistics and other discipline for arriving at an efficient and effective planning of experiments with a view to obtain valid conclusion from the analysis of experimental data. Design of experiments determines the pattern of observations to be made with a minimum of experimental efforts. To be specific Design of experiments (DOE) offers a systematic approach to study the effects of multiple variables / factors on products / process performance by providing a structural set of analysis in a design matrix. More specifically, the use of orthogonal Arrays (OA) for DOE provides an efficient and effective method for determining the most significant factors and interactions in a given design problem

B.   Principles of Design of Experiments

Design of Experiment (DOE) is a statistical approach that could clearly show how much several parameters of a system as well as their interactions are important on the plant output and how these parameters could affect the objective function. DOE Method is capable to investigate simultaneously the effects of multiple parameters on an output variable (response). To illustrate statistically reasonable conclusions from the experiment, it is necessary to integrate an efficient statistical method into the methodology of experimental design. In the context of DOE in designing, one may encounter two types of plant variables or factors: qualitative and quantitative factors. For quantitative factors, the range of settings must be decided by designer. For instance, pressure, temperature or heat transfer surface are examples of quantitative factors. Qualitative factors are discrete in nature. For example, types of materials, nature of heating source, and types of equipments are examples of qualitative factors. A factor may take different levels, depending on the character of the factor-quantitative or qualitative. In general, compared to a quantitative factor, more levels are required by a qualitative factor. "Level" in this chapter refers to a specified value or setting of the factor that would be examined in the plant experiment.(14)

C.   Minitab 16 Software for DOE

Meet Minitab introduces you to the most commonly used features in Minitab. Throughout the book, you use functions, create graphs, and generate statistics. The contents of Meet Minitab relate to the actions you need to perform in your own Minitab sessions. You use a sampling of Minitab's features to see the range of features and statistics that Minitab provides. Most statistical analyses require a series of steps, often directed by background knowledge or by the subject area you are investigating. Design of experiments (DOE) capabilities provide a method for simultaneously investigating the effects of multiple variables on an output variable (response). These experiments consist of a series of runs, or tests, in which purposeful changes are made to input variables or factors, and data are collected at each run. Quality professionals use DOE to identify the process conditions and product components that influence quality and then determine the input variable (factor) settings that maximize results. Minitab offers four types of designed experiments: factorial, response surface, mixture, and Taguchi (robust). The steps you follow in Minitab to create, analyze, and graph an experimental design are similar for all design types. After you conduct the experiment and enter the results, Minitab provides several analytical and graphing tools to help you understand the results. While this chapter demonstrates the typical steps for creating and analyzing a factorial design, you can apply these steps to any design you create in Minitab. Features of Minitab DOE commands include:

- Catalogs of experimental designs from which you can choose, to make creating a design easier
- Automatic creation and storage of your design once you have specified its properties
- Ability to display and store diagnostic statistics, to help you interpret the results
- Graphs that assist you in interpreting and presenting the results

We want to further improve the amount of time it takes to get orders to customers from the Western shipping center. After evaluating many potentially important factors, you decide to investigate two factors that may decrease the time to prepare an order for shipment: the order processing system and packing procedure. The Western center is experimenting with a new order processing system and you want to determine if it will speed up order preparation. The center also has two different packing procedures and we want to investigate which one is more efficient. You decide to conduct a factorial experiment to find out which combination of factors results in the shortest time to prepare an order for shipment. The results of this experiment will help you make decisions about the order processing system and packing procedures used in the shipping center.

D.   DOE by Response Surface Methodology (RSM)

In this section the basics of Response Surface Methodology (RSM) and how they work together with Design of Experiments methods is explained.

In many applications dependence between the input parameters and the output parameters of a complex system is unpredictable. RSM comprises a group of statistical techniques for empirical model building and model exploitation.

A second order model is generally used to approximate the response once it is realized that the experiment is close to the optimum response region where a first order model is no longer adequate. The second order model is usually sufficient for the optimum region, as third order and higher effects are seldom important.

$$y = \beta_0 + \beta_1 x_1 + \beta_1 x_1 + \beta_2 x_2 + \beta_k x_k + \beta_{11} x_1^2 + \ldots\ldots + \beta_{kk} x_k^2 + \varepsilon$$
(3.1)

The model contains regression parameters that include coefficients for main effects (β_1, $\beta_{2,\ldots}$ β_k), coefficients for quadratic main effects (β_{11}, $\beta_{22,\ldots}$ β_{kk}) and coefficients for two factor interaction effects (β_{11}, $\beta_{12,\ldots}$ $\beta_{k-1,k}$). A full factorial design with all factors at three levels would provide estimation of all the required regression parameters. However, full factorial three level designs are expensive to use as the number of runs increases rapidly with the number of factors. For example, a three factor full factorial design with each factor at three levels would require $2^3 = 27$ runs while a design with four factors would require $3^4 = 81$ runs. Additionally, these designs will estimate a number of higher order effects which are usually not of much importance to the experimenter. Therefore, for the purpose of analysis of response surfaces, special designs are used that help the experimenter fit the second order model to the response with the use of a minimum number of runs

For both input (x) and output parameters (y), transformations can be specified, so additional knowledge about the system behavior can be included. It should be noticed that a transformation for input parameters of the response surface should be used in the DOE step.

Additionally, it is also possible to automatically select the best out of a given set of transformation functions for a given set of sample points. This is done by computing several response surfaces where any possible variation of available transformations is applied to all input parameters. The selection criteria for the best set of transformations are determined by the minimum fit error of the sample points calculated by the total sum of squares of the residuals. For all these surfaces the fit error of the sample points (the sum of squares) is used to select the best combination of transformations.

E.   Box-Behnken Designs

Plackett-Burman designs are used to estimate main effects in the case of two level fractional factorial experiments using very few runs. G. E. P. Box and D. W. Behnken (1960) introduced similar designs for three level factors that are widely used in response surface methods to fit second-order models to the response. The designs are referred to as Box-Behnken designs. The designs were developed by the combination of two level factorial designs with incomplete block designs. For example, fig.3.1.
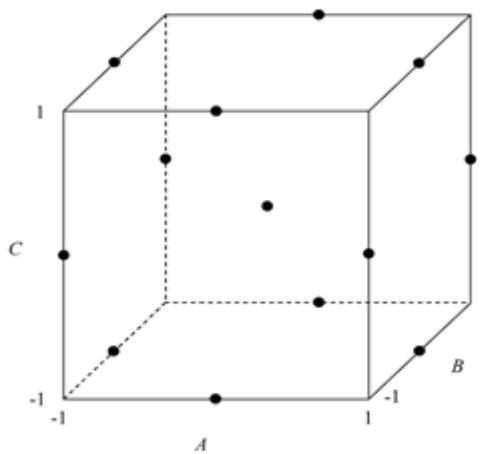

Fig.3.1: Box-Behnken design

The fig.3.1 shows the geometric representation of the design. The advantages of Box-Behnken designs include the fact that they are all spherical designs and require factors to be run at only three levels. The designs are also rotatable or nearly rotatable. Some of these designs also provide orthogonal blocking. Thus, if there is a need to separate runs into blocks for the Box-Behnken design, then designs are available that allow blocks to be used in such a way that the estimation of the regression parameters for the factor effects are not affected by the blocks. In other words, in these designs the block effects are orthogonal to the other factor effects. Yet another advantage of these designs is that there are no runs where all factors are at either the +1 or -1 levels.

IV. RESULT AND DISCUSSION

The ingredients effects on three friction characteristics including load, speed and track radius were studied by 2^k DOE. Concerning the confounding of two- ingredient interaction effects and main effects, response surface methodology was employed to optimize given parameter.

Table.4.1.Input variable.

	Lower limit	Upper limit
Load (kg)	1	4
Speed, (RPM)	200	1000
Track radius(mm)	40	120

Result On Minitab 16 for RSM
Box-Behnken Design
Factors: 3   Replicates: 1
Base runs: 15   Total runs: 15
Base blocks: 1   Total blocks: 1
Center points: 3

Table 4.2.Design Table

Run	Blk	A	B	C
1	1	+	-	0
2	1	0	0	0
3	1	-	+	0
4	1	-	-	0
5	1	0	-	-
6	1	0	-	+
7	1	-	0	-
8	1	0	+	-
9	1	0	+	+
10	1	0	0	0
11	1	0	0	0
12	1	+	+	0
13	1	+	0	-
14	1	-	0	+
15	1	+	0	+

Optimal Design: LOAD, SPEED, TRACK LENGH
Response surface design selected according to D-optimality
Number of candidate design points: 15
Number of design points in optimal design: 10
Model terms: A, B, C, AA, BB, CC, AB, AC, BC
Initial design generated by Sequential method
Initial design improved by Exchange method
Number of design points exchanged is 1
Optimal Design
Row number of selected design points: 8, 6, 12, 7, 14, 3, 1, 5, 2, 4
Condition number: 782.855
D-optimality (determinant of XTX):   4.15520E+48
A-optimality (trace of inv(XTX)):   44.3358
G-optimality (avg leverage/max leverage):   1
V-optimality (average leverage):   1
Maximum leverage: 1

A three-level factor consideration of saturated fractional factorial experiment design with resolution .The experiment design matrix, which was generated by the software of MinitabRel.16, was shown in Table.5.1. The low and high levels were design at ''-1'' and ''+1'', respectively.

Table.4.3. Optimum runs by RSM.

	C1 StdOrder	C2 RunOrder	C3 PtType	C4 Blocks	C5 LOAD	C6 SPEED	C7 TRACK LENGH
1	10	8	2	1	2.5	1000	40
2	11	6	2	1	2.5	200	120
3	4	12	2	1	4.0	1000	80
4	5	7	2	1	1.0	600	40
5	7	14	2	1	1.0	600	120
6	3	3	2	1	1.0	1000	80
7	2	1	2	1	4.0	200	80
8	9	5	2	1	2.5	200	40
9	15	2	0	1	2.5	600	80
10	1	4	2	1	1.0	200	80

The above runs performed before heat treatment and after heat treatment of each combination of heat treatments as CHT, HCT, HCTT, HCTTT.

V.   CONCLUSIONS

In the present work based on the characterization of cryotreated materials viz. D5 steel and selecting optimum parameter, the following conclusions are drawn:

Wear is main cause of material wastage, is an important problem associated with industrial component. The D 5 tool steel is high carbon high chromium (HCHCr) tool steel. This is promising tribological material with application of measuring tools, blanking dies, forming dies, coining dies, long punches, forming rolls, edging rolls, master tools, extrusion dies, drawing dies, etc

The configuration of pin material properties of D5 tool steel is studied and selected ranges for heat treatment temperature from Tool Steel handbook as and also selected disc material which should be higher than pin material.

The effect of different combination heat treatment like hardening within range of 996 C-1010 C for 1 hour, tempering within range of 177 C-316 C for 2 hours, Cryogenic treatment at -185 C for within range of 20 to 40 hours are will be carried out. Wear of pin with different load, speed and track radius are selected.

The speed, load and track radius are selected with lower and higher level .The optimum combination of all variables (speed, load, track radius) are selected by Response surface methodology (RSM) technique .This results shows optimum 10 runs before heat treatment and 10 runs for each combination of heat treatment as HCT, HCTT, HCTTT.

For study of variable and relation between wear rate and variable will going to plot by non-linear regression analysis.

REFERENCES

[1].   B. Podgornika, F. Majdicb, V. Leskovseka, J. VizintinbB. Podgornika, F. Majdicb, V. Leskovseka, J. Vizintinb "Improving tribological properties of tool steels through combination of deep-cryogenic treatment and plasma nitriding" Wear 288 (2012) 88– 93

[2].   D. Dasa, A.K. Duttab, K.K. Rayc," Influence of varied cryotreatment on the wear behavior of AISI D2 steel"; Wear 266 (2009) 297–309

[3].   L. Bourithis, G.D. Papadimitriou, J. Sideris; "Comparison of wear properties of tool steels AISI D2 and O1 with the same hardness"; Tribology International 39 (2006), pp 479-489.

[4].   Akhbarizadeh, A. Shafyei, M.A. Golozar; "Effects of cryogenic treatment on wear behavior of D6 tool steel"; Materials and Design 30(2009), pp 3259–3264.

[5].   K. Amini a, S. Nategh a, A. Shafyei b "Influence of different cryotreatments on tribological behavior of 80CrMo12 5 cold work tool steel"; Materials and Design 31 (2010) 4666–4675

[6].   N.B. Dhokey, S. Nirbhavne "Dry sliding wear of cryotreated multiple tempered D-3 tool steel"; journal of materials processing technology 2 0 9 (2 0 0 9) 1484–1490

[7].   Molinari, M. Pellizzari, S. Gialanella, G. Straffelini, K.H. Stiasny "Effect of deep cryogenic treatment on the properties of tool steel"Journal of Materials Processing Technology 118 (2001) 350-355

[8].   M. H. Staia, Y. Perez-Delgado, C. Sanchez, A. Castro, E. Le Bourhis, E.S. Puchi-Cabrera; "Hardness properties and high-temperature wear behavior of nitrided AISI D2 tool steel, prior and after PAPVD coating"; Wear 267 (2009), pp 1452-1461.

[9].   D. Dasa, A.K. Duttab, K.K. Rayc "Correlation of microstructure with wear behaviour of deep cryogenically treated AISI D2 steel"; Wear 267 (2009) 1371–1380

[10]. Foad Farhani a, Keyvan Seyedi Niaki a, Seyed Ebrahim Vahdat b,c, Amir Firozi "Study of effects of deep cryotreatment on mechanical properties of 1.2542 tool steel"; Materials and Design 42 (2012) 279–288

[11]. D. Dasa, K.K. Rayb, A.K. Duttac, "Influence of temperature of sub-zero treatments on the wear behaviour of die steel"; Wear 267 (2009) 1361–1370

[12]. Bahramia, S.H. Mousavi Anijdana, M.A. Golozarb, M. Shamanianb, N. Varahrama "Effects of conventional heat treatment on wear resistance of AISI H13 tool steel" ; Wear 258 (2005) 846–851

[13]. O. Barrau a, C. Boher, R. Gras b, F. Rezai-Aria a "Analysis of the friction and wear behavior of hot work tool steel for forging"; Wear 255 (2003) 1444–1454

[14]. J.D. Darwina, D. Mohan Lalb,1, G. Nagarajanb,1 "Optimization of cryogenic treatment to maximize the wear resistance of 18% Cr martensitic stainless steel by Taguchi method" ; journal of materials processing technology 1 9 5 (2 0 0 8) 241–247

[15]. Guipu Xiao , ZikangZhu "Friction materials development by using DOE/RSM and artificial neural network" , Tribology International 43 (2010) 218–227.

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