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To study wear characteristics of cryogenically treated T42 high speed steel

Prof. Ashish Bandewar[1], Prof. Nagesh Mathapati[2], Prof. Amol Kadam[3], Prof. Juned Kazi[4]

[1, 2, 3,4] Mechanical Engineering Department, Saraswati College of Enginering, Kharghar, Maharashtra, India

ABSTRACT

The word, "cryogenics" is taken from two Greek words - "kryos" Which means cold or freezing, & "genes" meaning born or generated. Technologically, it means the study & use of materials (or other requirements) at very low temperatures. In general cryogenic treatment consists of slow cooling already heat treated parts to approximately -196^0 C, holding at low temperature up to prescribed period, reheating without thermal shocks to room temperature & reheat to a moderately elevated temperature (150 to 315^0 C) for about 1 or 2 hours, to "temper" the part for the stated purpose of reducing its brittleness. In this study cryogenic treatment is performed on AISI T42 HSS material & its wear characteristics are studied. Test of treated & untreated samples is taken on pin on disc wear testing machine at different load & RPM. The wear of the sample is measured. The wear resistance of the samples is also measured by weight loss method. The results are tabulated. An experimental effort to evaluate tool wear improvement by cryogenic treatment is the outcome of this study.

Keywords: NOVA-Analysis of variance, T42 HSS, Taguchi, Cryogenic, wear resistance

1.INTRODUCTION

Freezing of metal has been acknowledged for many decades as an effective method for increasing wear life and decreasing residual stress in tool steels. Low temperature treatment is generally classified as either cold treatment at temperature down to approximately -80^0 c (dry ice temperature), or cryogenic treatment at -196^{0}c (liquid nitrogen temperature). It should be noticed that cooling & heating rates must be kept constant at an about 0.5^{o}C/min to avoid any thermal micro-cracking formation. Since the cryogenic treatment is normally done at very slow rates; it itself , relieves the brittleness & stress accumulation; however , low temperature tempering at 150-200 ^{0}c after cryogenic treatment is done to relieve any remained brittleness.

Two metallurgical phenomena are reported as the main reason for using cryogenic treatment. Firstly, the elimination on retained austenite and secondly the initiating of nucleation sites for subsequent precipitation of large number of very fine carbide particles.

In many cases hardness increasing about 1-3 Rockwell points have been claimed; however, some authors reported little increasing in hardness value. There is a little evidence concerning toughness changes. One of the most prevalent claims is the improvement of wear resistance. Some claims also have been made of improved uniformity of wear pattern, and also improved surface finish after grinding (Collins, 1996). Effect of cryogenic treatment on the matrix structure and abrasion resistance of high chromium cast iron subjected to destabilization. Heat treatment has been investigated by yang et al. (2006). They showed that during cryogenic treatment, the secondary carbides precipitate in the austenite matrix, promote the transformation of the retained austenite to martensite & consequently enhance hardness and wear resistance of the alloy. Zhirafar et al. (2007) have investigated the effect of cryogenic treatment on the mechanical properties & microstructure of AISI4340 steel. Following the result of neutron diffraction that the transformation of retained austenite to martensite occurred which along with possible carbide formation during tempering, is a key factor improving hardness & fatigue resistance of the cryogenically treated specimen.

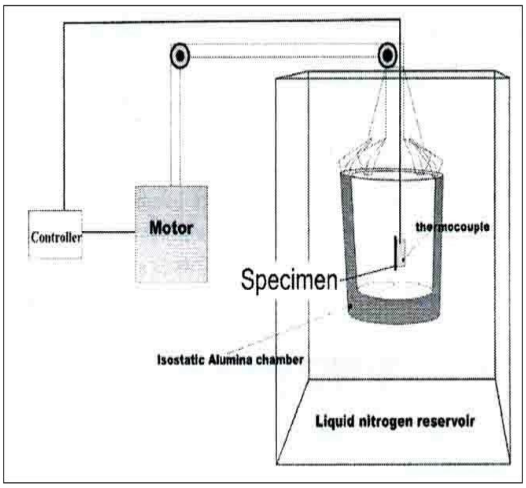

Fig1. *Cryogenic treatment system*

Cold treating is widely used for high precision parts & component, since it enhances the transformation of austenite to martensite. The component practice identifies -60 to -80C as the optimum temperature, according to material and the quenching parameters. Many companies use this kind of treatment to improve surface hardness & thermal stability.

Cryogenic treatment in the range of -125 to -196^0 C improves certain properties beyond the improvement obtained by normal cold treatment. The main reason for this is the complete transformation from austenite into martensite plus the formation of very small carbides dispersed in the tempered martensitic structure. The greatest improvement in the properties is obtained by carrying out the cryogenic treatment between quenching & tempering. However a significant improvement can be obtained even by treating the tool at the end of the usual heat treatment cycle i.e. the finished tools. This last solution is more flexible than the other one & can extend the use of the treatment to many practical applications.

2. EXPERIMENTAL DESIGN

Design of Experiments Using Taguchi Methods

2.1 Selecting the Levels for the Control Factors

In this study levels are selected by conducting screening experiments, brainstorming session with production experts, engineers and literature review. The range is selected between low and high levels of various parameters, load & RPM have been considered as process variables.

Table1.*Levels of operating parameters*

FACTORS	LEVEL-1	LEVEL-2	LEVEL-3
Load	2 kg	4 kg	6 kg
RPM	500	1000	1500

2.2 Selection of the Appropriate Taguchi Design

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L9 Orthogonal Array (OA) design have been selected. In this experiment, there are four parameters at three levels each. Experiments have been carried out using Taguchi's L9 Orthogonal Array (OA) experimental design which consists of 9 combinations of different controllable factors. L9 orthogonal array has been chosen because experimental trials required in this array is minimum in number.

For the experiment having four controllable factors with three levels, the standard factorial design requires 24 experiments to get 100 percent accurate result In comparison to above method orthogonal arrays instead of standard factorial design. This design reduces the number of experiments from24 (i.e. Factorial 4*3*2*1) to a designed set of 9 experiments. Those nine experiments will give 99.96% accurate result. By using this method number of experiments reduced to 9 instead of 24 with almost same accuracy.

Taguchi Orthogonal Array Design

L9 (2**3)

Factors: 2 Runs: 9

Table 2.*L9 (2*3) Orthogonal Array*

Trial Run.	load Level	RPM Level
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2

6	2	3
7	3	1
8	3	2
9	3	3

The set-ups are established according to the Taguchi design as shown above and experiments have been conducted.

3. METHODOLOGY

3.1Selection of Material for Test

AISI T42 material is selected because it exhibits certain desirable properties. These properties are listed below:

- The ability to resist softening at elevated temperature called as red hardness or the hot hardness;
- The resistance to wear of the tool area contacting the work - the wear resistance;
- The combination of strength and ductility.
- Higher hardness than that of the work piece material being machined, so that it can penetrate into the work material.
- Low friction: The coefficient of friction between the chip & tool material should be low.

3.2 Selection of Pin on Disc Wear Testing Machine:

Pin on Disc Wear Testing Machine is selected for experimentation.

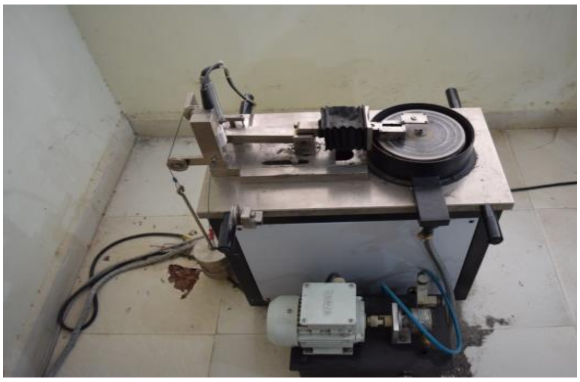

Fig 2. *Pin-on-disc wear testing Machine*

3.3 CRYOGENIC EQUIPMENT

Figure shows schematic representation of the cryogenic equipment. It comprises an insulated box (cryo box), one motor with a circulating fan, one thermocouple to measure the cryogenic temperature inside the box connected to a temperature controller & programmer, a liquid nitrogen tank & a solenoid valve for the gas inlet. The actual temperature of the mass loaded in the box is recorded by a thermocouple inserted in a 30 kg steel block.

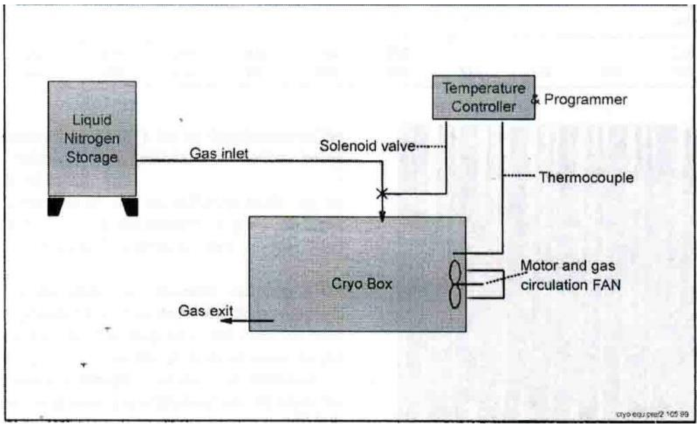

Fig 3. *Cryogenic equipment*

3.4 CRYOGENIC CYCLE

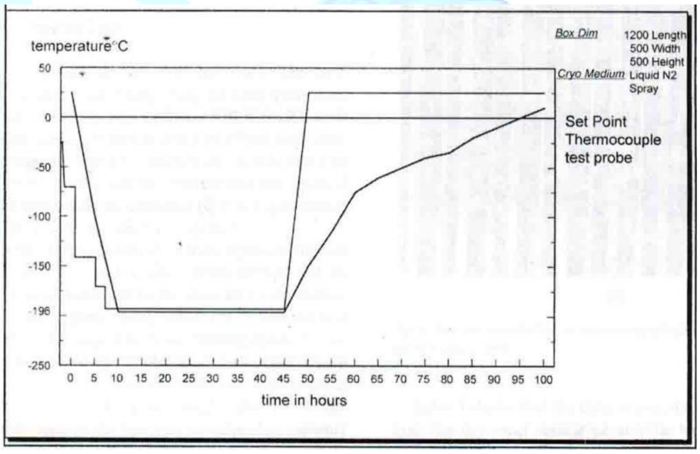

Fig 4. *Cryogenic cycle*

The thin & the bold lines represent the set up temperature & the test probe temperature, respectively. One of the most critical parameter is the cooling rate which must not exceed 20-30^0 C/h in order to prevent the rupture of the components because of the cooling stresses. The soaking time at the minimum temperature is about 35h; a more prolonged period does not have any significant effect. The total duration of the treatment is about 100 h.

3.5 CRYOGENIC TREATMENT SYSTEM

The cryogenic treatment is performed by placing the tools in an isolated alumina chamber immerged gradually in a liquid nitrogen reservoir by means of an electric motor. The isolated chamber is designed according to heat transfer equations to estimate the thermal gradient of the chamber. Cryogenic treatment consists of slowly cooling tools to approximately -196^0 C & holding at this low temperature for 24 h & gradually bringing the specimen back to room temperature. In order to avoid thermal shocks from rapid cooling &heating, the specimen were cooled down & heated up slowly, to & from the cryogenic temperature (-196 ^{0}C) over an eight period with the temperature being monitored by a thermocouple attached to the specimen. This gives an average heating/cooling rate of 0.5^0 C/min.

3.6 Heat Treatment & Cryogenic Treatment cycle performed on AISI T42:

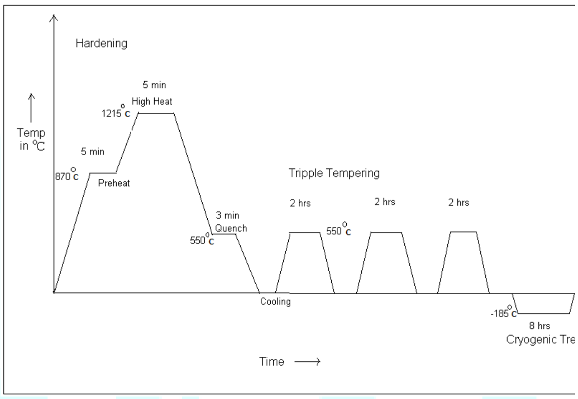

Fig 5. *Heat treatmet and cryogenic treatment cycle for AISI T42*

3.7 Procedure of Experimentation

1. To measure the weight of sample.

2. Setting the sample on pin on disc wear testing machine.

3. Starting the machine by setting the RPM, load, & time.

4. Machine stops after set time.

5. Removing the sample from machine.

6. Measuring the weight of sample.

7. Weight loss is calculated.

8. From this weight loss wear rate is calculated.

Wear Rate = weight loss / (density X time)

3.8 Signal-to-noise ratio for Response Characteristics

The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments.

Controllable factors are divided into 3 main types:

Those which affect the average levels of the response of interest, referred to as Target Control Factors (TCF), sometimes called signal factors. In this thesis work they are load & RPM. and Temperature Those which affect the variability in the response, the Variability Control Factors (VCF). Those which affect neither the mean response nor the variability, and can thus be adjusted to fit economic requirements, called the cost factors. At the heart of Taguchi philosophy is the quality loss function. The loss function promotes efforts to continually reduce the variation in a product's functional characteristics. The change in quality characteristic of a product under investigation in response to a factor introduced in the experimental design is the 'signal' of the desired effect. The effect of the external factors (uncontrollable factors) on the outcome of quality characteristic is termed as 'noise'. The objective of any experiment is to achieve the best possible S/N ratio. Finding a correct objective function to maximize in an engineering design problem is very important. Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Higher the Better:

(S/N)HB= -10 log (MSDHB)

Where

$$MSDHB=\frac{1}{R}\sum_{i=1}^{R}\left(\frac{1}{Yi}\right)^2$$

MSDHB=Mean Square Deviation for higher-the-better response

Lower the Better:

(S/N)LB= -10 log (MSDLB)

Where

$$SDLB = \frac{1}{R}\sum_{i=1}^{R}(Yi)^2$$

MSDHB =Mean Square Deviation for Lower-the-better response

Nominal the Better:
(S/N)NB= -10 log (MSDNB)
Where,

$$MSDNB = \frac{1}{R}\sum_{i=1}^{R}(Yi - Y0)^2$$

MSDHB =Mean Square Deviation for Nominal-the-better response

Yi = Observed value of the response characteristic
Y0 = nominal or target value of the results
R = Number of repetitions

4. RESULTS AND DISCUSSION

Experimental results based on Taguchi parametric design

Using Taguchi design, L9 orthogonal array has been selected & experiments were performed according to the set of combinations of factors as given in L9 orthogonal array for finding out levels for final experimentation. Various factors for this study were load, RPM etc. For all these parameters, three levels of variation were selected. After the experimental results have been obtained, analysis of the results was carried out analytically as well as graphically. For graphical analysis of the experimental results plots, showing effects of all the factors upon responses, are generated in Minitab. Then ANOVA of the experimental data has been done to calculate the contribution of each factor in response. The response to be considered is wear rate. After studying the effect of all the factors on the response, signal to noise ratio has been calculated for wear rate. Then optimal conditions have been calculated for wear rate. Experiments are performed according to the selected design of experiment as shown in table below. All the data recorded were used in the subsequent analysis.

***Table3**. Taguchi L9 orthogonal Array*

Load	RPM	Time in minutes
2	500	6.37
2	1000	3.18
2	1500	2.12
4	500	6.37
4	1000	3.18
4	1500	2.12
6	500	6.37
6	1000	3.18
6	1500	2.12

***Table: 4**. Wear Rate values obtained in first run*

Load	RPM	Time in minutes	Wear Rate
2	500	6.37	1.67
2	1000	3.18	1.7
2	1500	2.12	2.76
4	500	6.37	0.853
4	1000	3.18	2.36
4	1500	2.12	2.76
6	500	6.37	2
6	1000	3.18	2.36
6	1500	2.12	4.73

***Table 5**: wear Rate values obtained in second run*

Load	RPM	Time in minutes	Wear Rate
2	500	6.37	1.378
2	1000	3.18	2.564
2	1500	2.12	2.465
4	500	6.37	1.5
4	1000	3.18	1.775
4	1500	2.12	3.944
6	500	6.37	1.7
6	1000	3.18	3.22
6	1500	2.12	5.52

***Table 6**: wear Rate values obtained in third run*

Load	RPM	Time in minutes	Wear Rate
2	500	6.37	0.754
2	1000	3.18	2.63
2	1500	2.12	2.86
4	500	6.37	1.5
4	1000	3.18	2.23
4	1500	2.12	2.76
6	500	6.37	2.33
6	1000	3.18	2.76
6	1500	2.12	4.73

***Table 7**: Average wear rate values obtained in all runs*

EXPT RUN	Load	RPM	Time in min.	WR1	WR2	WR3	Avg. Wear Rate
1	2	500	6.37	1.67	1.378	0.754	1.267
2	2	1000	3.18	1.7	2.564	2.63	2.298
3	2	1500	2.12	2.76	2.465	2.86	2.695
4	4	500	6.37	0.853	1.5	1.5	1.284

5	4	1000	3.18	2.36	1.775	2.23	2.45
6	4	1500	2.12	2.76	3.944	2.76	3.154
7	6	500	6.37	2	1.7	2.33	2.01
8	6	1000	3.18	2.36	3.22	2.76	2.78
9	6	1500	2.12	4.73	5.52	4.73	5

Wear rate is calculated by using the following formula:
Wear Rate = weight loss / (density x time)

Variation in the wear rate is observed in three runs, this is because of following reasons-

- Chemical decomposition of samples
- Diffusion of samples on disc
- Difference in homogeneousness of samples
- Hardness variation
- Experimental error

4.1 Analysis using S/N ratio

This section discusses S/N ratio analysis which is the most important part of Taguchi method. The Taguchi method stresses the importance of studying the response variation using the signal -to-noise(S/N) ratio, resulting in minimization of quality characteristics variation due to uncontrollable parameters. The results obtained from experiments & measurements of wear rate are shown in Table 8. WR1, WR2, WR3 refers to the response (wear rate) in the first, second & third replications respectively. It also shows the arithmetic average values & S/N ratio for the wear data.

***Table 8**: Experimental Results for Wear Rate*

EXPT. RUN	WR1	WR2	WR3	Avg. Wear Rate	S/N Ra
1	1.67	1.378	0.754	1.267	-2.055
2	1.7	2.564	2.63	2.298	-7.227
3	2.76	2.465	2.86	2.695	-8.611
4	0.853	1.5	1.5	1.284	-2.171
5	2.36	1.775	2.23	2.45	-7.783
6	2.76	3.944	2.76	3.154	-9.977
7	2	1.7	2.33	2.01	-6.0639
8	2.36	3.22	2.76	2.78	-8.8809
9	4.73	5.52	4.73	5	-13.9794

S/N ratio is calculated by following formula:
Lower the Better:
(S/N)LB= -10 log (MSDLB)
Where MSDLB $=\frac{1}{R}\sum_{i=1}^{R}(Yi)^2$
MSDHB =Mean Square Deviation for Lower-the-better response

4.1.3 Effect of Load and RPM on wear rate.
Figure 6 to 8 shows the graphs of RPM vs. Wear rate and figure 9 to 11 shows the graph of Load vs. Wear rate

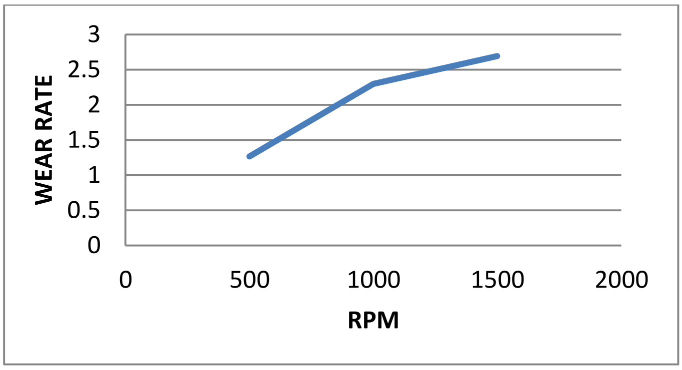

***Fig.6** RPM VS WEAR RATE*

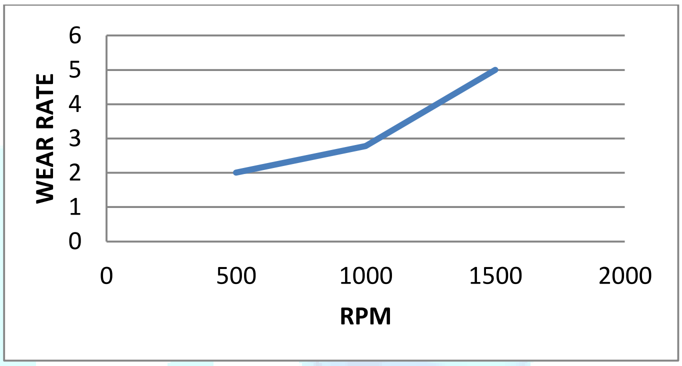

***Fig.7** RPM VS WEAR RATE*

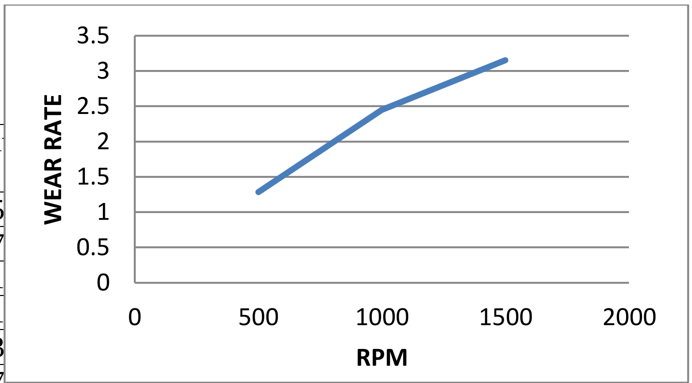

***Fig.8** RPM VS WEAR RATE*

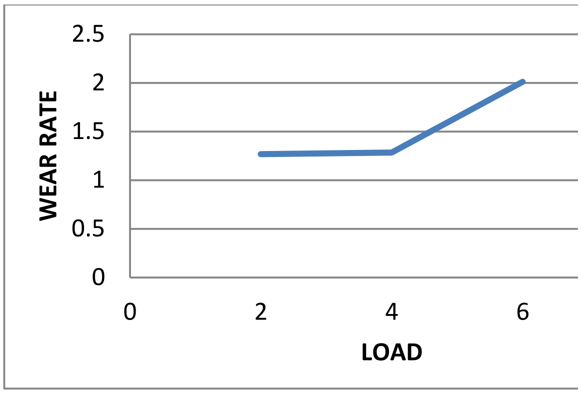

Fig.9 *LOAD VS WEAR RATE*

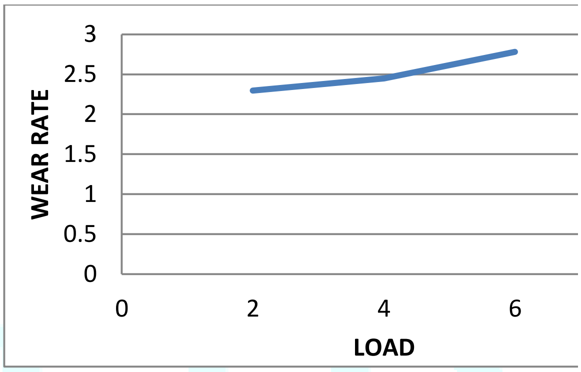

Fig.10*LOAD VS WEAR RATE*

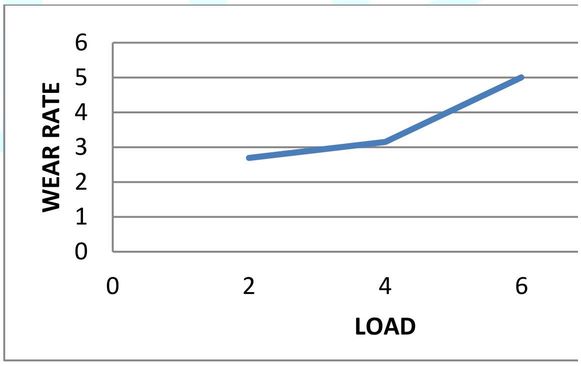

Fig.11 *LOAD VS WEAR RATE*

1. The graph between RPM and wear rate shows that at the RPM increases, the wear rate increases.

2. The graph between load and wear rate shows that as the load increases the wear rate increases

3. The variation in wear rate is observed in the graph. The reason for this is that when the speed & load is increased, the level of energy or temperature is increased sharply, as there is not enough time for heat dissipation. Thus temperature of sample edge area goes on increasing causing more erosion of the sample particles, increasing wear of tool sharply.

4.3 Significance of factors using S/N Ratio Analysis:

Table 9*: Response table for S/N Ratios*

	Level	Load	RPM
Mean S/N ratio	1	-5.965	-3.430
	2	-6.644	-7.964
	3	-9.641	-10.856
	Delta	3.677	7.426
	Rank	2	1

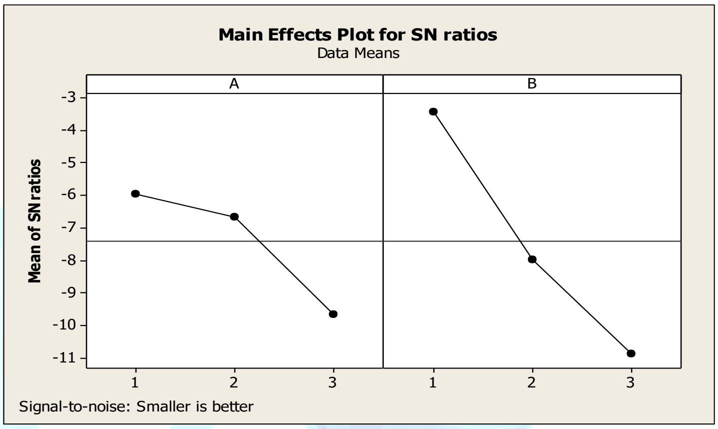

Fig.12 *Main effects plot for SN ratios*

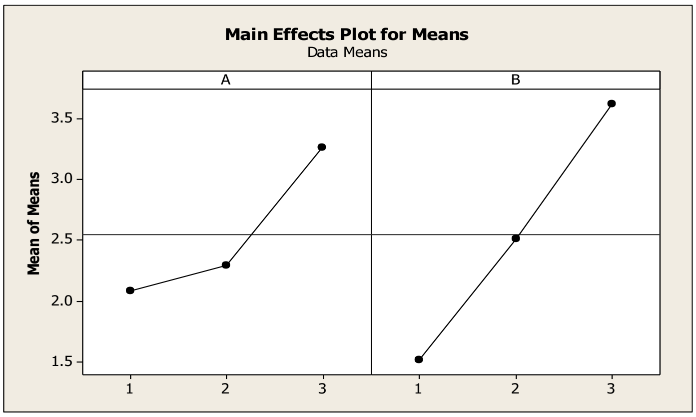

Fig.13 *Main effect plot for Means*

After performing the experiment for load of 2kg to 6kg, RPM 500 to 1500 respectively the response values of wear rate are obtained from 9 combinations of runs. By analyzing the response, above table is obtained. Significance of parameters for wear rate was determined by signal to noise ratio as shown in above table. Significance of parameter (difference between max & min values) indicates the RPM is significantly contributing towards the performance; Therefore RPM is most influencing parameter for optimizing wear rate. The signal to noise ratio analysis showed that optimized process parameters corresponding to wear rate are

- Load= 2Kg
- RPM=500

4.4 Analysis of variance (ANOVA)

Table 10 gives the ANOVA and F test values with percentage contribution of each factor. Taguchi method cannot judge & determine the effect of individual parameters on entire process while percentage contribution of individual parameter can be well determined using ANOVA. Analysis of variance is a method of portioning variability into identifiable sources of variation & the associated degree of freedom in an experiment. The frequency test (F-test) is utilized in statistics to analyze the significant effects of the parameters, which form the quality characteristics. The ANOVA result for wear rate is illustrated in Table. F-value for wear rate & the contribution of the process parameters load & rpm were calculated. The results of ANOVA for the wear rate are shown in Table 10. This analysis is carried out for a significant level. The main effect of RPM (the most significant parameter), load (significance below the RPM) are significant.

***Table 10** Analysis of variance for wear Rate*

source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
Load	2	2.3641	2.3641	1.1820	4.32	0.004	23.51
RPM	2	6.5968	6.5968	3.2984	12.06	0.0035	65.60
Error	4	1.0943	1.0943	0.2736			
Total	8	10.0552					

From the values of above table it is evident that 65.60% RPM is contributing on wear rate than other parameters. The load is next contributing factor whose contribution is 23.511%.The similar results are obtained from Taguchi method, signal to noise ratio analysis as well as ANOVA analysis. RPM is found to be the most significant parameter & second significant parameter is load which has the significant effect on wear rate.

4.5 Regression Analysis

Multiple linear regression equations were modeled for a relationship between process parameters in a bid to evaluate tool wear for any combinations of factor levels in a range specified .methods for fitting into a linear regression models are least square regression, ridge regression and Bayesian regression. When predictor variables are correlated, least square estimates of regression coefficients tend to have larger sampling variability. In such a situation, ridge regression offers a method to obtain better estimates of regression coefficients. Partial least square regression technique can also be used for multi co linearity. Bayesian regression provides multiple linear regression models.

Multiple regression equations obtained from regression analysis for wear rate obtained from Minitab 16 software are as follows:

Wear Rate = -0.724 + o.588 load + 1.05 RPM

4.5 Discussion

From the results, it can be seen that the wear of cryo treated samples is less as compared to the wear of non cryo treated samples. The wear of cryo treated samples in some cases is observed as half of non cryo treated samples. This low wear sample is an indicator of improved tool life. The improvement in wear resistance of the samples is basically due to conversion of retained austenite to martensite and precipitation of carbides.

The AISI T42 samples were subjected to experimentation on pin-on-disc wear testing machine to calculate wear rate. From experimentation it is seen that RPM is the most significant parameter & second significant parameter is load which has the significant effect on wear rate.

5.CONCLUSION

From the analysis of the result using the conceptual signal-to-noise (S/N) ratio approach, analysis of variance (ANOVA), regression analysis & Taguchi optimization method, the following can be concluded from the present study:

1. The wear resistance of cryo treated samples improves as compared to the non-treated samples.
2. From the results, it can be seen that the wear of cryo treated samples is less as compared to the wear of non cryo treated samples. This low wear of the sample is an indicator of improved life.
3. The improvement in wear resistance of the samples is basically due to conversion of retained austenite to martensite & precipitation of the carbides.
4. The similar results are obtained from Taguchi method, signal to noise ratio analysis as well as ANOVA analysis.
5. Significance of parameters indicates that RPM is significantly contributing towards performance Therefore; most influencing parameter is RPM. The second influencing parameter is load.
6. RPM is found to be the most significant parameter & second significant parameter is load which has the significant effect on wear rate.
7. The results of ANOVA for wear rate show that 65.60586% RPM is contributing on wear rate than other parameter. The load is the next contributing factor whose contribution is 23.60586%.

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