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Parameters Optimization in the Experimental Wear Study on ADI at Elevated Temperature

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***Abstract*— The progression in today's innovation requires the use of unrivaled material. Austempered Ductile Iron (ADI) is one such promising material offering better combination of strength and ductility. The present study investigates the influence of applied load, sliding speed and temperature on wear rate of ADI austenitised at 870°C for 120 min. and austempered for 180 mins. at 380°C. The dry sliding wear tests were performed with DUCOM pin-on-disc machine. The experiments were conducted for a constant sliding distance of 2500 m. The chosen parameters impact on the wear rate was examined by Taguchi's technique utilizing Design of Experiments. For the examination of information an L_9 orthogonal array was chosen. S/N ratio and ANOVA decided positioning and rate impact of parameters on wear rate. Results show that load is the highest influencing parameter followed by temperature and sliding speed. Worn out wear surfaces were analyzed using scanning electron microscope.**

***Keywords*—Austempered Ductile Iron, Load, Elevated temperature, Optimization, Speed, Wear behaviour**

I. INTRODUCTION

Currently there is a great deal of interest in the wear of metals and materials throughout the world. Superior wear resistant materials with low friction coefficients are being investigated for a range of applications. Nowadays metals or alloys possessing light weight, good mechanical and tribological properties with lower costs have great demand. This resulted in the development of one of the high strength materials know as Austempred Ductile Iron (ADI). The materials holds superior ductility, fatigue resistance, toughness, hardness and wear resistance properties. It is 10% light in weight with 20% less production cost when contrasted with steel. Worldwide market segments for ADI include: heavy vehicle, light vehicle, construction, agriculture, railroad, mining and miscellaneous industrial applications.

The key application of ADI is in automotive sector. ADI is made by subjecting ductile iron to austempering heat treatment. This results in ausferrite microstructure [1, 2]. Amid the previous couple of years, ADI has got much revelation. So far it remained a very misunderstood material. For several years steel metallurgy encumbered the development of ADI [3]. One of the routes by which a material fizzles is by wear and 33% of the world's vitality is used in beating erosion in either frame. Consequently there is a more prominent accentuation to comprehend the wear conduct of ADI to improve its application regions. There are various approaches to study wear like dry sliding test (pin or ball type), abrasion test, scratch test etc. The most admired among these methods is the dry sliding wear test. Numerous analysts dealt with ADI to comprehend its conduct. Yet at the same time there is a more prominent extent of research on this rising material as it is wrapped with superb property blends required for different applications. Gears, pinions, crankshafts and comparable parts require enhanced wear resistance of ADI prompts interests in their wear conduct [4, 5]. Islam et al. [5] studied the dry sliding wear of ductile iron in the as-cast, quenched, tempered and austempered conditions. He found that matrix of bainitic ferrite and carbon enriched austenite resulted by autempering heat treatment proved to be a better combination of strength and toughness compared to quenched and tempered ductile iron. Velez et al. [6] and Mohan et al. [7] showed that ADI with fine ausferrite shows greater wear resistance than quenched and tempered iron of similar hardness. Ahmadabadi et al. [8] reported that ADI with 0.75 wt.% Mn austempered at 315°C has higher wear resistance than that austempered at 375°C. Daber et al. [9, 10] have reported that the blocky austenite in ausferrite produced at higher austempering temperature is prone to undergo strain induced transformation to martensite.

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ADI is a promising material to be utilized under wear conditions and accordingly it is generally utilized as a part of utilizations, for example, gears, pinions, crankshafts, affect plates, jaw crusher segments, hammers, excavator teeth, bores and rolls, horticultural actualizes and vehicle and motor parts large portions of these parts are subjected to rubbing and wear, which makes this iron exceptionally fascinating from the tribological conduct perspective [11-13]. The sliding wear behaviour of ADI, has been studied by several researchers; according to Haseeb et al. [11], the wear resistance under dry sliding conditions of ADI is superior to a quenched and tempered steel with the same hardness level. Uma et al. [12], also under dry sliding conditions by using pin-on-disk machine, have reported that the wear loss is related to the original hardness (before the wear test) but also suggested that the strain hardening of austenite provides significant improvement in wear resistance. In addition, Asiabi et al. [14] have highlighted that the maximum wear resistance in these irons is observed when the retained austenite is maximum and also when the tempering temperature is low.

There have been numerous one of a kind procedures in this day and age to draw out the streamlined outcome on each investigation and examination. One such is the Taguchi's Technique which is broadly utilized as a part of the field of wear investigation to concentrate the wear conduct materials. The tribological conduct of glass epoxy polymer composites with silicon carbide and graphite particles, as auxiliary fillers, was considered utilizing a pin-on-disc wear analyzer under dry sliding conditions [15]. The works carried out on simultaneous optimization of multiple quality characteristics by fuzzy logic and Taguchi's technique have proven to be a successful and easy method [16]. Apte et al. [17] optimized Electrical Discharge Machining process parameters using Taguchi method. Radhika et al. [18] studied the influence of various parameters such as load, sliding speed and temperature on the dry sliding wear behaviour of AlSi10Mg alloy reinforced with 3 wt% graphite and 9 wt% alumina fabricated through liquid metallurgy route.

In light of the above writing, to enhance the dry sliding wear resistance for the applications expressed above and to deliver better contrasting option to different metals particularly for cast press made car segments where light weight and wear resistance was under real thought, ADI was created for wear consider. It was solutionenized at 870°C for 120 minutes and austempered at 380°C for 180 minutes. The dry sliding wear examinations were directed in view of the arrangement produced by Taguchi strategy.

The impact of different parameters on the wear rate was examined utilizing Signal-to-Noise (S/N) proportion and Analysis of Variance (ANOVA).

II. Taguchi Technique

Design of Experiments (DOE) was employed for analyzing the impact of assorted input parameters on a given output. DOE approach makes use of Taguchi technique to find the optimal blend of parameters for a given set of response [19]. It provides an optimized depiction to improve the performance, efficiency and cost. This method was utilized for assessing frameworks in view of orthogonal arrays. The method was largely used because of its ability to examine and interpret data based on the responses. A typical orthogonal array was chosen based on the number of parameters, and the consequence of parameters on the target value. The dissimilarities were identified by means of a signal to- noise ratio. This S/N ratio provides the effect of noise on various characteristics. ANOVA was used to establish the percentage of control of various parameters on the response [20]. It was a quantitative measurement to decide the contribution of each parameter on the rejoinder.

III. Experimental Details

The dry sliding wear test was led on a pin-on-disc analyzer as appeared in fig. 1. Size of the specimen used for the wear test was of 30 mm in length and 10 mm in diameter. They were machined and polished as per ASTM standards. The experiment was performed by holding the pin against a turning disc (EN32 steel) and by adding weights on the left arm of the machinery. The track diameter of 120mm and sliding distance of 2500m were chosen for study. The experiment was then accomplished by differing the applied load, temperature and sliding speed for three levels as shown in Table 1.

Figure 1. Pin-on-disc wear tester

Table 1.
Parameters and their levels

Level	Load [N]	Sliding speed [m/s]	Temperature [°C]
1	9.81	1.75	100
2	19.62	3.25	150
3	29.43	5.50	200

IV. PLAN OF EXPERIMENTS

Experiments were carried out by considering these three parameters by varying them for three levels. The degree of freedom for an orthogonal array was chosen as 9, based on the tenet that it should be greater than the wear parameters considered (Table 2).

Table 2.
Orthogonal array

Expt. No.	Load [N]	Sliding speed [m/s]	Temperature [°C]
1	9.81	1.75	100
2	9.81	3.25	150
3	9.81	5.50	200
4	19.62	1.75	150
5	19.62	3.25	200
6	19.62	5.50	100
7	29.43	1.75	200
8	29.43	3.25	100
9	29.43	5.50	150

The grouping for the cluster relies upon the quantity of components drew in, levels and their responses. The primary segment was taken as the load, the second as the sliding speed and third temperature. The S/N ratio combines all multiple data and approximates them based on the characteristics of the data.

The S/N ratio was by and large grouped into three sorts: "smaller the better", larger the better" and "normal the best". “Smaller the better” characteristic of S/N ratio was deemed for minimum wear rate and is given by:

$$\eta = -\frac{1}{n}\log_{10}\{\sum_{i=1}^{n} y_i^2\}\text{---------------}(1)$$

Where $y_1, y_2 \ldots y_n$ were the response and n is the number of observations. ANOVA was performed to determine the percentage effect of each parameter.

V. RESULTS AND DISCUSSION

The control parameters were analyzed using Minitab software, especially intended for this purpose. S/N ratio and ANOVA were calculated.

A. Analysis using S/N ratio

Experiments were performed according to the orthogonal array and the observed values of wear rate are shown in Table 3. The influence of control parameters on wear rate were found using S/N ratio. The parameter with the highest S/N ratio gives minimum wear rate. The response table for S/N ratio is shown in Table 4. The contrast between the greatest and least estimations of S/N ratio gives delta. Positioning of parameter were finished by the delta esteem. The parameter with the largest value of delta has the greatest influence on wear rate [21]. From Table 4, it was found that load has the significant impact on wear rate followed by temperature and sliding speed.

The main effects plot for means is shown in fig.2. From the plot, it is concluded that wear rate increases with increase in applied load and temperature. Conversely, the wear rate decreases with increase in sliding speed at room temperature but increases with speed at higher temperatures. As the temperature builds, the material winds up plainly milder and consequently more material has been expelled from the wear surface.

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Table 3.
Orthogonal array of Taguchi for wear rate and experimental results

Expt. No.	Load [N]	Sliding Speed [m/s]	Temperature [°C]	Wear rate [m^3/m] x10^{-12}	S/N ratio [dB]	COF	S/N ratio [dB]
1	9.81	1.75	100	0.0062	44.15	0.2854	10.89
2	9.81	3.25	150	0.0135	37.39	0.2650	11.54
3	9.81	5.50	200	0.0355	29.00	0.2446	12.23
4	19.62	1.75	150	0.0175	35.14	0.3415	9.33
5	19.62	3.25	200	0.0428	27.37	0.3211	9.87
6	19.62	5.50	100	0.0208	33.64	0.3160	10.01
7	29.43	1.75	200	0.0541	25.34	0.4621	6.71
8	29.43	3.25	100	0.0400	27.96	0.4825	6.33
9	29.43	5.50	150	0.0456	26.82	0.4757	6.45

Table 4.
Response table for S/N ratio-wear rate

Level	Load [N]	Sliding speed [m/s]	Temperature [°C]
1	36.85	34.88	35.25
2	32.05	30.91	33.12
3	26.71	29.82	27.23
Delta	10.14	5.06	8.02
Rank	1	3	2

Table 5.
Response table for S/N ratio-COF

Level	Load [N]	Sliding speed [m/s]	Temperature [°C]
1	11.552	8.976	9.076
2	9.735	9.244	9.107
3	6.496	9.563	9.601
Delta	5.056	0.587	0.525
Rank	1	2	3

Table 6.
Analysis of Variance for wear rate

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P-value	P (%)
Load (L)	2	154.434	154.434	77.217	22.69	0.042	50.28
Speed (S)	2	42.511	42.511	21.256	6.25	0.138	13.83
Temperature (T)	2	103.414	103.414	51.707	15.20	0.062	33.67
Error	2	6.805	6.805	3.403			2.22
Total	8	307.163					100

(Notes: DF, Degrees of freedom; Seq SS, Sequential sum of squares; Adj SS, Adjusted sum of squares; Adj MS, Adjusted mean squares; P, Percentage of contribution.) R-Sq = 97.81% R-Sq(adj) = 91.23%

Table 7.
Analysis of Variance for COF

Source	DOF	Seq SS	Adj SS	Adj MS	F-test	P-value	P (%)
Load (L)	2	39.3568	39.3568	19.6784	213.24	0.005	96.98
Speed (S)	2	0.5186	0.5186	0.2593	2.81	0.262	1.28
Temperature (T)	2	0.5212	0.5212	0.2606	2.82	0.262	1.27
Error	2	0.1846	0.1846	0.0923			0.45
Total	8	40.5812					100

(Notes: DF, Degrees of freedom; Seq SS, Sequential sum of squares; Adj SS, Adjusted sum of squares; Adj MS, Adjusted mean squares; P, Percentage of contribution.) R-Sq = 96.10% R-Sq(adj) = 84.40%.

$$Wear\ rate\ (m^3/m)=(-0.0373+0.00144*L+0.00204*S+0.000218*T)10^{-12} \text{--(2)}$$
$$COF = 0.191+0.0106*L-0.00469*S-0.000187*T \text{ ----------------------------(3)}$$

The main effects plot for S/N ratio was shown in Fig. 3. The input process parameter value which has the highest S/N ratio gives the optimum wear rate. From the Figure, it was found that L=9.81 N, S=1.75 m/s and T=100 °C gives the optimum condition. Figure 6 depicts the variation of frictional force with time.

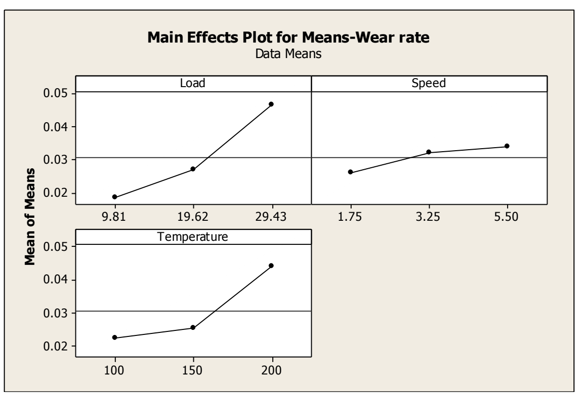

Figure 2. Main effects plot for means-wear rate

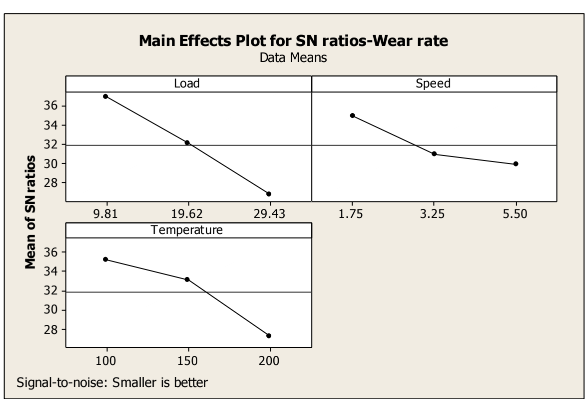

Figure 3. Main effects plot for S/N ratios-wear rate

B. Analysis of Variance

ANOVA was exercised to analyze the influence of control parameters like applied load, sliding speed and temperature on wear rate. The investigation was performed for a level of significance, α=0.05. The ANOVA for wear rate is shown in Table 6. The last column in the table indicates the percentage involvement of each input process parameter on the wear rate. It shows that load (50.28 %) has the greatest contribution on wear rate followed by temperature (33.67 %) and sliding speed (13.83 %).

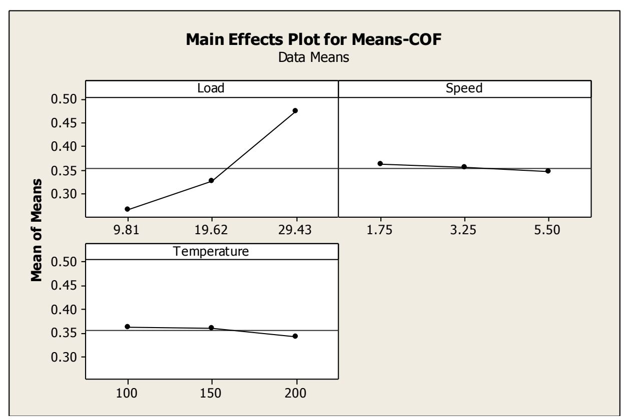

Figure 4. Main effects plot for means-COF

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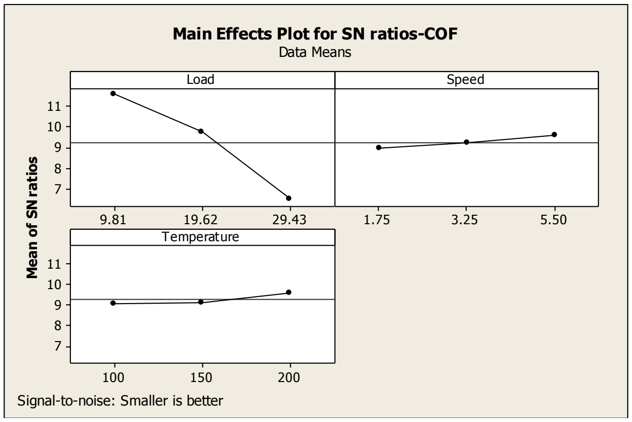

Figure 5. Main effects plot for S/N ratios-COF

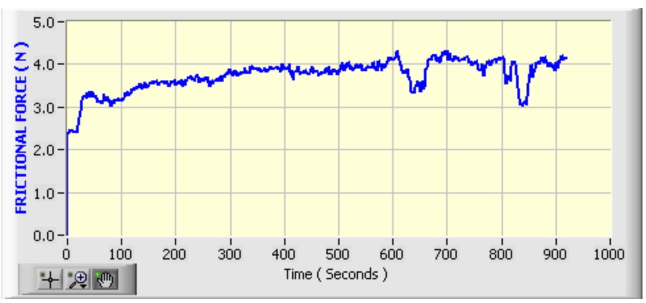

Figure 6. Variation of Frictional force with time

C. Regression Analysis and Confirmation Test

A linear regression model was developed based on the experimental results. It establishes a correlation between the important parameters. The regression equation developed for wear rate is given by equation 2.

From the relation, it is observed that the coefficient associated with load, speed and temperature is positive. This clearly reveals that as load, speed and temperature increase, wear rate of ADI also increase. To approve the conclusions acquired from the investigation, affirmation analysis was led and correlation was made between the experimental and computed values created from regression model. Table 8 shows the parameters of confirmation test and 9 show the confirmation test results.

It is noticed that the error between experimental and computed values is minimal and hence this regression model can be used successfully to predict the wear rate of ADI with good accuracy.

Table 8.
Parameters for confirmation experiment

Expt. No.	Load [N]	Sliding speed [ms^{-1}]	Temperature [°C]
1	14.715	1.5	80
2	24.525	3.0	120
3	34.335	4.5	170

Table 9.
Results of confirmation experiment

Expt. No.	Experimental wear rate [m^3/m] x 10^{-12}	Regression model wear rate [m^3/m] x 10^{-12}	Error [%]
1	0.0045	0.0044	2.22
2	0.0315	0.0303	3.81
3	0.0603	0.0562	6.80

D. Scanning Electron Microscopy Analysis

The SEM micrographs of worn-out surfaces for various conditions are shown in figures 7, 8 and 9.

From the SEM Micrograph (fig. 7), it was found that at low applied load, sliding speed and temperature, the worn pin surface shows material removal in the direction of sliding by delamination [23]. The carbon on the surface appeared as black spots. At higher loads (fig. 8), the soft surface particles get fractured and these particles acts as sharp asperities to remove more material from the wear surface forming shallow grooves [22].

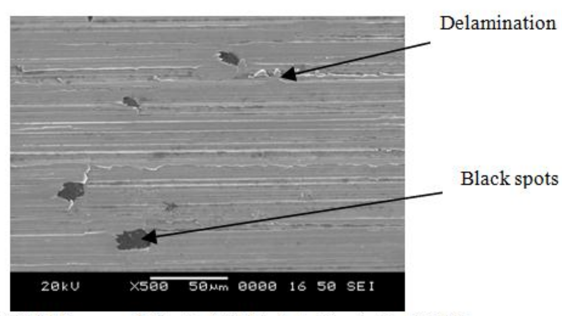

Fig. 7. SEM Micrograph for L=9.81 N, S=1.75 m/s, T=100 °C.

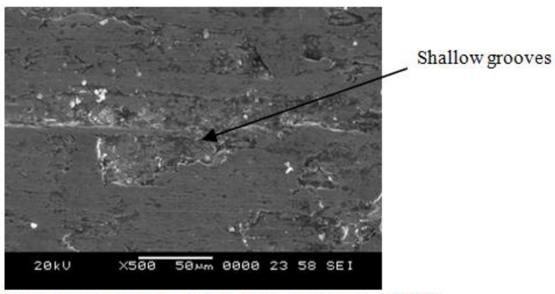

Fig. 8. SEM Micrograph for L=19.62 N, S=1.75 m/s, T=150 °C.

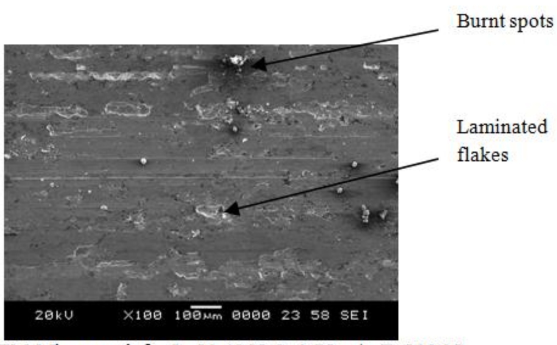

Fig. 9 SEM Micrograph for L=29.43 N, S=1.75 m/s, T=200 °C.

Also at high load and temperature, the material undergoes severe plastic deformation forming hot spots. These burnt locations were subjected to high stresses and got peeled off from the surface resulting in severe wear. The temperature and load together reduce the work hardening capabilities of the material making it prone for wear. This indicates the non-suitability of the material for elevated temperature applications.

VI. Conclusions

The experiments were conducted as per the run order generated by Taguchi technique and the conclusions can be summarized as follows.

- Optimal setting for minimum wear rate were obtained using S/N ratio analysis and ANOVA. The analysis shows that wear rate increases with increase in applied load, temperature and speed. From the main effects plot for means and S/N ratio, it was found that L=9.81 N, S=1.75 m/s and T=100 °C gave minimum wear rate.
- The ANOVA shows the percentage involvement of each control parameter on wear rate. From the S/N ratio and ANOVA analysis, it was noticed that applied load has the highest implication on wear rate followed by temperature and sliding speed. The regression model generated was efficiently used to predict the wear rate.
- Scanning Electron Microscopy analysis of the worn-out surfaces have shown burnt spots of high plastic deformation regions making the location soft. The material got removed from them by adhesion to the disc resulting in shallow grooves.
- The material is subjected to severe wear at higher temperatures when compared to room temperature for the given load and speed rendering the material non-suitable for elevated temperature applications.

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