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Full Length Research Paper

Applications of taguchi design method to study wear behaviour of boronized AISI 1040 steel

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In this study, AISI 1040 steel was boronized using the packed boronizing technique. Processes were carried out at the temperature of 950℃ for 2 and 4 h of treatment. The wear resistance model for AISI 1040 steel was developed in terms of boronizing time, applied load, sliding distance and sliding speed using the Taguchi method. Wear tests were carried out using a pin-on-disc type of apparatus under different conditions. The orthogonal array, signal-to-noise (S/N) ratio and analysis of variance are employed to investigate the optimal testing parameters. The experimental results demonstrate that the boronizing time was the major parameter among the controllable factors that influence the weight loss of AISI 1040 steel. For AISI 1040 steel, the boronizing time had the greatest effect on the wear, followed by sliding distance. The applied load and sliding speed had a much lower effect. The optimal combination of the testing parameters could be determined. A good agreement between the predicted and actual weight loss was observed within ±3.5%.

Key words: Taguchi method, boronizing, wear test.

INTRODUCTION

Boronizing is a thermo-chemical diffusion process in which boron is diffused into the steel at high temperatures. Surfaces of boronized irons and steels have high hardness, excellent wear resistance, good corrosion resistance and strong chemical stability (Pelleg et al., 1992; Kaljakjian, 1995; Yu et al., 2002; Jain and Sundararajan, 2002). Boron atoms are diffused into the surface of work piece to form hard borides with the base material (Carbucicchio and Palombarini, 1987; Carbucicchio et al., 1980, Biddulph, 1977). Boronizing is a prominent choice for a wide range of tribological applications where the control of friction and wear is of primary concern (Erdemir and Bindal, 1995). The boronizing process could be applied to a wide range of materials including ferrous materials, nonferrous materials and some super alloys (Jain and Sundararajan, 2002). Boronizing of ferrous materials is generally performed at temperatures ranging from 840 to 1050℃ (Sahin, 2009).

Boronizing is one of the methods used to improve steel and iron surface properties. Boronized steel constituents show excellent performance in several tribological applications in the mechanical engineering and in the automotive industries (Martini et al., 2004). The pack boronizing is used commonly for commercial purposes among these methods, higher treatment temperatures and a longer period of time constitutes its drawbacks (Biddulph and Leonhardt, 1999; Ozbek et al., 2002). The powder-pack boronizing has the advantages of simplicity and cost-effectiveness in comparison with other boronizing processes. In this technique, the boronizing agent in powder form is placed into a heat resistant box and samples are embedded into this powder under inert gas atmosphere (Keddam and Chentouf, 2005).

Different studies have been carried out on the wear behaviour of various steels using experimental or theoretical work. The following is merely a brief overview of the work reported in the literature.Tabur et al. (2009) studied abrasive wear behaviors and mechanical properties of AISI 8620 steels, both unboronized and boronized at different temperatures for different treatment times. The results show that the specimen boronized has higher wear resistance than the specimen carburised.

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Table 1. Chemical compositions of 1040 and 440C steels (wt. %).

Steels	C	Cr	Ni	Si	Mn	Mo	S	P
AISI 1040	0.39	0.16	-	0.189	0.76	-	0.015	0.035
AISI 440C	0.91	16.5	0.318	0.42	0.417	0.46	0.001	0.0024

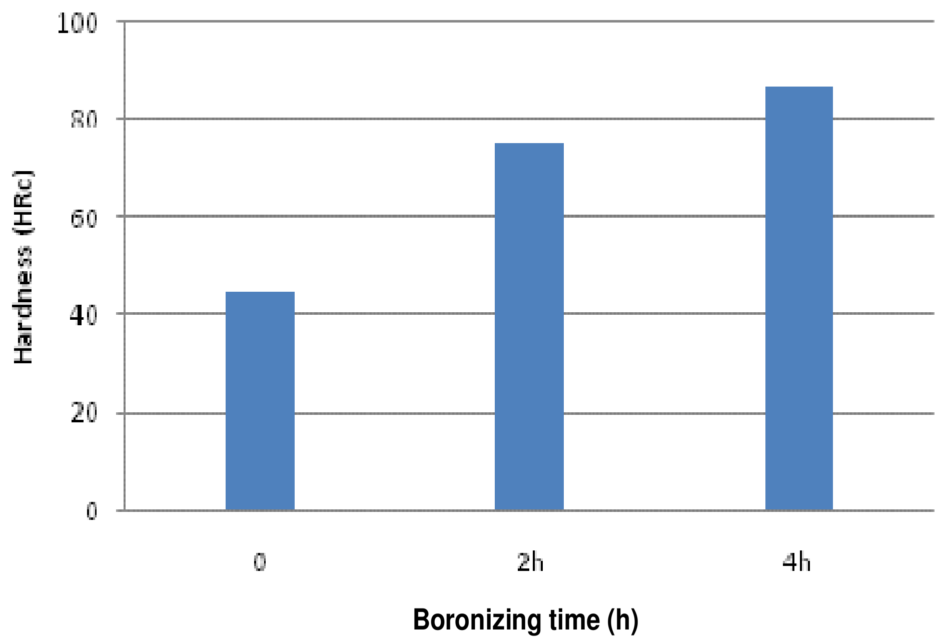

Figure 1. The hardness values of the AISI 1040 with different boronizing time.

Venkataraman and Sundararajan (1995) reported the high speed sliding wear behaviour of boronized medium carbon steel. The sliding wear rate is reduced by about an order of magnitude when the steel is boronized. Ribeiro et al. (2006) investigated the friction and wear properties of boronized niobium, which are important in order to find its feasibility as implant material. They suggested that the application of boride coatings on the niobium surface can reduce the friction and wear in biological applications. Bejar and Moreno (2006) investigated the abrasive wear resistance of previously boronized carbon and low-alloy (AISI 1020, 1045, 4140 and 4340) steels.

The experimental results exhibit that boronized 1020 steel exhibited the greatest abrasive wear resistance. Sahin (2006) developed the wear resistance model for low-carbon (AISI 1020), carbon (AISI 1340) and low alloyed (AISI 5150) steels in terms of abrasive grain size, normal load and sliding distance using the Taguchi method. He observed that theoretical values differed from the experimental value within ±10%. From the above literature survey, it is seen that most of the study has been concentrated on the experimental work for wear behaviour of boronized steels, and a few mathematical models based on statistical regression techniques has been reported.

The goal of this study is to investigate the wear behaviour of boronized AISI 1040 steel based on the Taguchi method under various testing conditions and boronizing time.

WEAR TEST AND EXPERIMENTAL DESIGN

Wear test

The test pin material made of AISI 1040 steel was used for the present study. AISI 440C steel was used as a material for the test disk. Wear test specimen were machined from boronized samples to form cylindrical pins having a diameter of 6 mm and a length of 10 mm. The specimen faces were then metallographically polished. The chemical composition of AISI 1040 and 440C steels are shown in Table 1. Figure 1 shows the hardness values for boronized AISI 1040 steel. The figure shows that the hardness value increases almost linearly with the boronizing time. The dry sliding wear tests were conducted using a pin-on-disc apparatus (Figure 2) at room temperature regarding the ASTM G99-95 standards. The details of the wear test conditions are given in Table 2.

The counter body is a disc made of ground stainless steel (AISI 440C, hardness 63hRC, surface roughness 0.24 µm). The specimen is held stationary and the disc is rotated while a normal

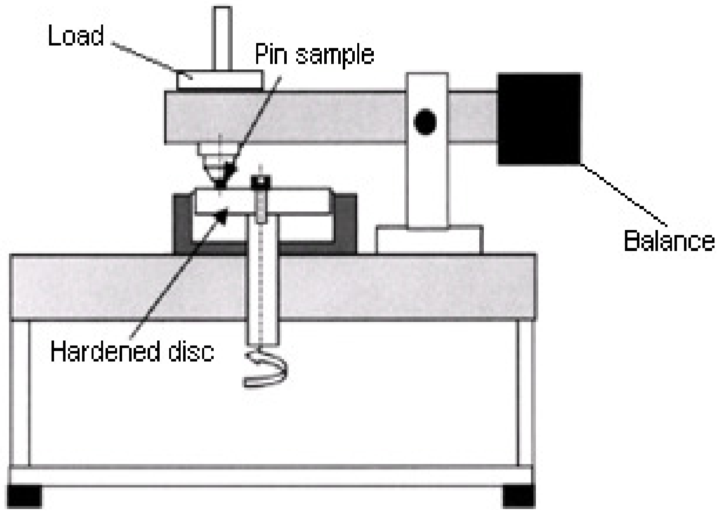

Figure 2. The schematic diagram of the pin on disc apparatus used in this study.

Table 2. Details of the wear test conditions used in this study.

Pin material	AISI 1040 steel
Disc material	AISI 440C stainless steel with a hardness of 63 HRc
Pin dimensions	Cylinder with diameter 6mm and height 10mm
Sliding speeds (m/s)	0.5-1.0-1.5
Normal loads (N)	30,60,120
Sliding distance (m)	150,300,600

Table 3. Control factors and their levels.

Control factor	Level			
	I	II	III	Units
A:Boronizing time	Unboronized	2 h	4 h	hour
B:Normal load	30	60	120	N
C:Sliding distance	150	300	600	m
D:Sliding speed	0.5	1.0	1.5	m/s

force is applied through a lever mechanism. Three sliding velocities of 0.5, 1.0 and 1.5 m/s under three different normal loading of 30, 60 and 1200 N are used for conducting wear tests. A precision electronic balance with accuracy ±0.001 mg is used to find the material loss from the specimen surface during sliding wear test. After the test, the specimen was removed, cleaned with acetone and weighed to determine the weight loss. The difference in weight gives the wear of the specimen.

Experimental design

The experiments were carried out to analyse the influence of testing parameters on weight loss of boronized steels. The levels of control parameters were shown in Table 3. This table shows that the experimental plan had three levels. A standard Taguchi experimental plan with notation L27 (3^{13}) was chosen (Table 4). In the Taguchi method, the experimental results are transformed into a signal-to-noise (S/N) ratio. This method recommends the use of S/N ratio to measure the quality characteristics deviating from the desired values. There are three categories of quality characteristic in the analysis of the S/N ratio, that is the-lower-the-better, the higher-the-better, and the-nominal-the-better.

To obtain optimal testing parameters, the-lower-the-better quality characteristic for weight loss was taken. The S/N ratio for each level of testing parameters was computed based on the S/N analysis. Moreover, a statistical analysis of variance (ANOVA) was performed to see which test parameters are statistically significant. With S/N ratio and ANOVA analyses, the optimal combination of the testing parameters could be predicted for a 95% confidence level.

Table 4. Experimental lay out and results with calculated S/N ratios for weight loss of AISI 1040 steel.

Boronizing time (h)	Normal load (N)	Sliding distance (m)	Sliding speed (m/s)	weight loss (mg)	S/N ratios (dB)
Unboronized	30	150	0.5	420.00	-52.46
Unboronized	30	300	1	529.20	-54.47
Unboronized	30	600	2	679.14	-5664
Unboronized	60	150	1	485.10	-53.,72
Unboronized	60	300	2	609.84	-55.70
Unboronized	60	600	0.5	679.14	-56.64
Unboronized	120	150	2	577.50	-55.23
Unboronized	120	300	0.5	630.00	-55.99
Unboronized	120	600	1	810.34	-58.17
2	30	150	1	64.85	-36.24
2	30	300	2	81.53	-38.23
2	30	600	0.5	90.79	-39.16
2	60	150	2	67.94	-36.64
2	60	300	0.5	74.12	-37.40
2	60	600	1	95.33	-39.58
2	120	150	0.5	61.78	-35.82
2	120	300	1	77.84	-37.82
2	120	600	2	99.89	-39.99
4	30	150	2	45.29	-33.12
4	30	300	0.5	49.41	-33.88
4	30	600	1	63.56	-36.06
4	60	150	0.5	41.18	-32.29
4	60	300	1	51.88	-34.30
4	60	600	2	66.58	-36.47
4	120	150	1	43.24	-32.72
4	120	300	2	54.35	-34.70
4	120	600	0.5	60.53	-35.64

Table 5. The S/N response table for wearing of boronized AISI 1040 steel.

Level	A	B	C	D
1	-55.45	-42.25	-40.92	-42.14
2	-37.88	-42.53	-42.5	-42.57
3	-34.35	-42.9	-44.26	-42.97
Delta	21.09	0.65	3.35	0.83
Rank	1	4	2	3

RESULTS AND DISCUSSION

Analysis of control factor

Table 4 shows experimental layout and results with the calculated S/N ratios for weight loss of the AISI 1040 steel. Analysis of the influence of each control factor on the weight was performed with a so-called S/N response table, using a Minitab 15.1 computer package. The response table of the testing process is presented in Table 5. The control factor with the strongest influence was determined by difference values. The higher the difference, the more influential was the control factor or an interaction of two controls. The strongest influence was found out by material boronizing time (A) and sliding distance (C), respectively. The main effects and their interaction plots for S/N ratios are shown in Figures 3 and 4. Optimal testing conditions of these control factors can

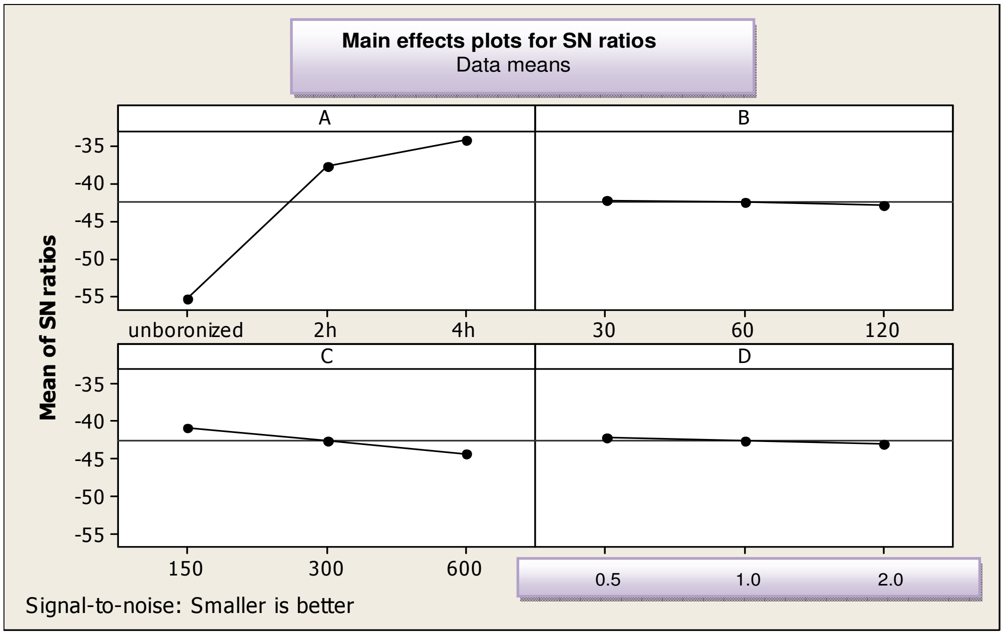

Figure 3. Main effects plots for S/N ratios.

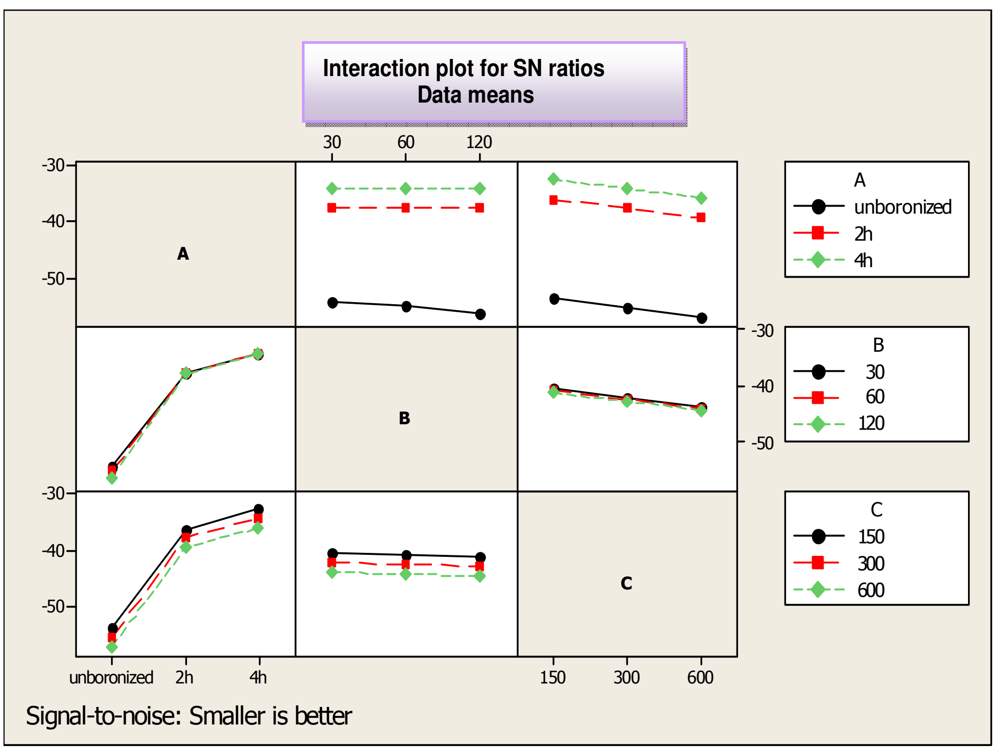

Figure 4. Interaction effects plots for S/N ratios.

be easily determined from this graph.

A response graph showed the change of the S/N ratio for various control factor levels. The best weight loss value was at the higher S/N values in the response graphs. It could be seen in Figure 3 that the initial optimum condition for the tested samples becomes

Table 6. Results of variance analysis for weight loss of AISI 1040 steel.

Source	DF	SDQ	Variance	Test *F*	F_{Table}	P^{a}(%)
A	2	1727788	863894	4328	14,54[b]	93,96
B	2	8698	4349	21,79	14,54[b]	0,47
C	2	39395	19698	98.69	14,54[b]	2,14
D	2	1757	879	4.4	3,46[c]	0,10
A*B	4	17123	4281	21.45	14,54[b]	0,93
A*C	4	41781	10445	52.33	14,54[b]	2,27
B*C	4	1045	261	1.31		0,06
Error	6	1198	200			
Total	26	1838783				

SDQ: Sum of squares; DF: degrees of freedom; *P*: percentage of contribution. [a] percentage of contribution. [b] 99.5% confidence level. [c] 90% confidence level.

A3B1C1D1 for main control factors. It is evident that the boronizing time had the greatest effect on the optimal testing condition. The weight loss obviously decreased as boronizing time increased from 2 to 4 h. It is well know that hardness of boride layer plays important role in improvement of the wear resistance (Selcuk et al., 2003; Atik et al., 2003; Li et al., 2008). The relationship between the surface hardness and wear rates of the boronized samples also confirms that the wear resistance is improved with the hardness increasing (Yan et al., 2002; Mu et al., 2010).

In addition, weight loss increased with the sliding distance. Similar results were also reported by Selcuk et al. (2003), Meric et al. (2006), and Yilmaz et al. (2010). By increasing sliding distance a decrease in boride layer thickness is seen. This situation is led to a decrease in wear resistance of boronized sample and deformed.

Analysis of variance

The analysis of variance (ANOVA) is used to investigate which design parameters significantly affect the quality characteristic. It is accomplished by separating the total variability of the S/N ratios, which is measured by sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the errors. Examination of the calculated values of variance ratio (F), which is the variance of the factor divided by the error variance for all control factors showed a much higher influence of factor A and high influence of factor C on the wear of AISI 1040 steel (Table 6).

The last column of the above table indicates the percentage of each factor contribution (P) on the total variation, thus exhibiting the degree of influence on the result. It may be observed in this table that the boronizing time factor (P ≈ 94%), and the sliding distance (P ≈ 2.15%) had a significant influence on the weight loss of AISI 1040 steel while applied load (P = 0.47%) and sliding speed (P = 0.10%) had a much lower effects on it. The interactions AxB (P ≈ 0.95 %), AxC (P ≈ 2.27%) and BxC (P ≈ 0.06%) do not present percentages of physical significance of contribution on the weight loss.

Confirmation tests

The final step was to verify the improvement of the quality characteristic using the optimal levels of the design parameters (A3B1C1D1). The S/N ratio was calculated as the following equation, selecting the optimal levels of control factors;

$$\hat{\eta}_i = \eta_m + \sum_{i=0}^{N}(\eta_i - \eta_m)$$

Where η_m is the total mean S/N ratio, η_i is the mean S/N ratio of the results at the optimal level and N is the number of the main design parameters that affect the quality characteristics (Ross, 1996). According to this prediction, it could be inferred that the S/N ratio was found to be -31.98 dB. It was corresponded to about 39.70 mg, which was the smaller value within the obtained experimental results (Table 7).

This table shows the comparison of the predicted weight loss with the actual weight loss using the optimal testing parameters, a good agreement between the predicted and actual weight loss being observed. Therefore, based on the S/N ratio and ANOVA analysis, the optimal testing parameters for the weight loss for samples were the factor A at 3 level, factor B at level 1, the factor C at level 1 and factor D at 1 level. If the difference $|\eta_{i,ver} - \eta_{i,cal}|$ is in both cases within the interval limit, the model is adequate. Table 7 shows that there was a much lower difference between the theoretical and experimental results.

Conclusions

AISI 1040 steel samples were boronized by the solid-state

Table 7. Results of the confirmation experiments for weight loss of boronized AISI 1040 steel.

	Optimal control parameters		
	Prediction ($\eta_{i,cal}$)	Experimental ($\eta_{i,ver}$)	Difference $\lvert\eta_{i,ver}-\eta_{i,cal}\rvert$
Level	$A_3B_1C_1D_1$	$A_3B_1C_1D_1$	
Weight loss (mg)	39,7	41,176	1.476
S/N ratio for weight loss(dB)	-31.98	-32.29	0.31

pack boronizing method and the wear behaviour of the test specimens with different boronizing time was investigated using pin-on-disc machine. The L27 (313) orthogonal arrays were adopted to investigate the effects of boronizing time, normal load, sliding distance and sliding speed on weight loss of AISI 1040 steel. The ANOVA results showed that the boronizing time exerted the greatest effect on the wear, followed the sliding distance. The confirmation experiments were conducted to verify the optimal testing parameters. It is observed that there was good agreement between the predicted and actual wear loss within 3.5% significant level. In addition, the boronized samples led to more wear resistance than those of unboronized samples. Moreover, the percentage contribution of boronizing time and sliding distance was about 93.96 and 2.14%, respectively.

As a result, it is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the wear test parameters.

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