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Optimizing mean effective case depth of induction hardened parts (rolled condition) using response surface methodolgy

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ABSTRACT : An effective procedure of response surface methodology (RSM) has been utilized in this paper for finding optimal values of process parameters for mean effective case depth in induction hardening of AISI 1040 in rolled condition. Various process parameters such as feed rate, current, dwell time and gap between the work piece & induction coil, are explored by experiments. The experimental plan was based on rotatable central composite design (CCD). The experimental results show that the proposed mathematical model could describe the performance indicator within the limits of the factors being investigated. The optimal value for mean effective case depth obtained was 3.09 mm at the optimal settings of the process variables. The results have been verified by confirmation experiments.

Keywords : Induction Hardening, Central composite design, Design Expert software, Response surface methodology

NOMENCLATURE

R^2	=	Coefficient of determination
Adeq. Precision	=	Adequate precision
Adj R^2	=	Adjusted R^2
CV	=	Coefficient of variation
df	=	Degrees of freedom
Pred. R^2	=	Predicted R^2
Prob. >F	=	Probability to get the stated F value
PRESS	=	Predicted residual error sum of squares
MECD(R)	=	Mean effective case depth as rolled condition of the material.

I. INTRODUCTION

Suitable thermal, mechanical, and thermo-mechanical surface engineering treatments are required for a corresponding marked variation in physical, chemical and mechanical properties, and rearrangement of atoms in metals and alloys. The heat treatment processes such as gas carburizing and induction hardening are among the more important of such treatments [1]. Kayacan investigated the effect of distance between coil and material, cooling time, applied power and frequency, on the performance of induction hardening process. He compared optimized fuzzy solution of the induction hardening process with the experimental results and found good agreement between the two [2,3]. Many mechanical parts, such as shafts, gears, springs etc. are subjected to surface treatments before the actual delivery in order to improve their wear behaviour [4]. Y. Totik. *et. al.,* investigated the effects of heating time (feed rate) and temperature on wear characteristics of AISI 4140 steel in induction hardening process [5] and Julie [6] studied the effects of feed rate, gap between coil and workpiece, quench distance and part temperature, using design of experiment and neural network approach on induction hardening process and reported a significant improvement in the process.

In this paper, the mean effective case depth of induction hardened parts in rolled condition has been optimized using response surface methodology (RSM). This is because RSM is one of the most widely used methods to solve the optimization problem in the manufacturing environments [7-10]. Since time and money are involved while performing the experimental runs, it is pertinent to reduce the number of runs while not compromising the desired goals. For the achievement of the above mentioned objectives, some strategies like central composite designs in RSM have been frequently used [11].

II. EXPERIMENTAL SETUP

A. Experimental apparatus

For performing the experiments, the medium frequency induction hardening machine (10 KHz, 120 KW and Spindle speed 400 r.p.m.), make “Unitherm” is used. Maximum job holding length of the machine is 50.8 mm.

A source of high frequency electricity is used to drive a large alternating current through a copper coil. The passage of current through this coil generates a very intense and rapidly changing magnetic field in the space within the work coil. The workpiece to be heated is placed within this intense alternating magnetic field where eddy currents are generated within the workpiece and resistance leads to Joule heating of the metal. The core of the component remains unaffected by this treatment.

B. Work piece material

The depth of hardening performance tests after induction hardening at rolled condition were performed on

AISI 1040 steel bars. The composition of the material is ascertained as 0.45% C, 0.75% Mn, 0.20% Si, 0.05% S and 0.07% P, 0.12% Cr, 0.15% Cu using glow discharge spectrometer. The length of the workpiece and diameter are 304.8 mm and 25 mm respectively. The material chosen is suitable for a wide variety of automotive components like gears, axle, crankshafts and spline shafts [12].

C. Experimental plan

In this investigation four factors were studied and their low and high levels are given in Table 1. The levels were selected after performing the pilot runs. Rotatable central composite design (CCD) has been used to carry out the experiments.

Table 1 : Factors and levels for response surface study.

Factors	Low level(-1)	High level(+1)
Feed rate(mm/s)	2	4
Dwell time(sec)	5	7
Current(Ampere)	125	135
Gap between workpiece and inductor coil(mm)	5	7

Based upon the foregoing inputs, the complete design layout produced by the software Design Expert Version 7.1.6 (Stat-Ease Inc., Minneapolis, and 185 MN USA) is given in Table 2.

Table 2 : Experimental Data for mean effective case depth.

Std run no	Run	Block	Feed rate A(mm/s)	Dwell time B(sec)	Current C (Amp)	Gap D (mm)	MECD R (mm)
1	21	1	2	5	125	5	2.12
2	29	1	4	5	125	5	2.22
3	30	1	2	7	125	5	2.39
4	3	1	4	7	125	5	1.8
5	28	1	2	5	135	5	3.32
6	18	1	4	5	135	5	2.4
7	24	1	2	7	135	5	3
8	16	1	4	7	135	5	2.05
9	7	1	2	5	125	7	2.4
10	19	1	4	5	125	7	1.8
11	5	1	2	7	125	7	2.52
12	13	1	4	7	125	7	1.86
13	12	1	2	5	135	7	3
14	1	1	4	5	135	7	1.74
15	25	1	2	7	135	7	2.9
16	15	1	4	7	135	7	1.38
17	22	1	1	6	130	6	2.16
18	4	1	5	6	130	6	1.2
19	26	1	3	4	130	6	2.4
20	6	1	3	8	130	6	1.92
21	8	1	3	6	120	6	2.77
22	2	1	3	6	140	6	3.14
23	27	1	3	6	130	4	2.52
24	14	1	3	6	130	8	1.32
25	9	1	3	6	130	6	2.23
26	17	1	3	6	130	6	2.1
27	23	1	3	6	130	6	2.05
28	20	1	3	6	130	6	2.1
29	11	1	3	6	130	6	2.05
30	10	1	3	6	130	6	1.8

(Contd...)

As given in Table 2, performance tests involved 30 trials and the mean effective case depth was measured.

III. RESULTS AND DISCUSSIONS

The mean of three values of effective case depth for each trial is reported in Table 2. The analysis of results was done using the software.

Table 3 : ANOVA table for the response at rolled condition.

Source	Sum of Squares	df	MeanSquare	FValue	p-valueProb > F	
Model	7.59	14	0.54	19	< 0.0001	significant
A-Feed Rate	2.01	1	2.01	70.38	< 0.0001	
	0.18	1	0.18	6.46	0.022	
C-Current	0.62	1	0.62	21.61	0.0003	
D-Gap	0.37	1	0.37	12.85	0.0027	
AB	0.26	1	0.26	9.08	0.0087	
AC	0.24	1	0.24	8.25	0.0116	
AD	0.31	1	0.31	10.81	0.0050	
BC	4.197E-003	1	4.197E-003	0.15	0.7066	
BD	1.922E-004	1	1.922E-004	6.738E	0.9357	
CD	0.074	1	0.074	2.60	0.1277	
A^2	0.063	1	0.063	2.20	0.158	

(Contd...)

Source	Sum of Squares	df	MeanSquare	*F*-Value	*p*-valueProb > *F*	
B^2	5.869E-004	1	5.869E-004	0.021	0.887	
C^2	1.12	1	1.12	39.13	<0.0001	
D^2	0.066	1	0.066	2.33	0.147	
Residual	0.43	15	0.029			
Lack of Fit	0.33	10	0.033	1.67	0.296	not significant
Pure Error	0.098	5	0.020			
Cor Total	8.02	29				

Std. Dev. 0.17, *R*-Squared 0.946, Mean 2.22, Adj *R*-Squared 0.896, C.V. % 7.60, Pred *R*-Squared 0.718, Press 2.26, Adeq Precision 17.90

A. Analysis of variance (ANOVA)

ANOVA table is used to summarize the test for significance of regression model, test for significance for individual model coefficient and test for lack of fit. Summary output reveals that quadratic model is statistically significant for the selected response. Significant model terms were identified at 95% significance level. Goodness of fit was evaluated from R^2 and CV in order to check the reliability and precision of the model. The ANOVA table, by selecting the manual procedure for the response at rolled condition, is given as Table 3.

The probability > F for the model in Table 3 is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. In this case *A*, *B*, *C*, *D*, *AB*, *AC*, *AD*, *BC*, *BD*, *CD*, A^2, B^2, C^2, D^2 are significant model terms. Model fitting with the help of Design-Expert software suggested that a quadratic model provides the best fit, and the model was found to have insignificant Lack of fit. This is desirable as a model that fits is desirable. The ANOVA table for quadratic model indicated that the model is significant at $p < 0.0001$, and its Lack of fit, 1.67, is not significant. The R^2 value is high and close to one, which is desirable. The value of $R^2 = 94.6\%$ explains that this much percentage of the variability of result is explained by the model. The predicted R^2 value of 0.718 is in reasonable agreement with the adjusted R^2 of 0.896. Adequate precision measures signal to noise ratio and is computed by dividing the difference between the maximum predicted response and the minimum predicted response by the average standard deviation of all predicted responses. Ratios greater than 4 are desirable. In this particular case the value is 17.90, which is well above 4. This indicates that an adequate signal is there to use this model for navigating the design space. PRESS stands for "Predicted residual error sum of squares" and it is a measure of how well the model for the experiment is likely to predict the responses in new experiments. Small values of PRESS are desirable. In this case the value is 2.26.

The equation 2 and 3 are the final empirical models in terms of coded (standardized) and actual factors (un-standardized) for the response in rolled condition.

Final equation in terms of coded factors :

$$\text{MECD(R)} = +2.08 - 0.40 \times A - 0.12 \times B + 0.20 \times C - 0.17 \times D - 0.12 \times A \times B - 0.13 \times A \times C - 0.15 \times A \times D - 0.015 \times B \times C + 3.503E - 003 \times B \times D - 0.075 \times C \times D - 0.055 \times A2 - 4.272E - 003 \times B2 + 0.30 \times C2 - 0.059 \times D2 \quad ...(2)$$

Final equation in terms of actual factors :

$$\text{MECD(R)} = +170.21 + 5.02 \times \text{feed rate} + 0.682 \times \text{dwell time} - 2.88 \times \text{current} + 2.933 \times \text{gap} - 0.124 \times \text{feed rate} \times \text{dwell time} - 0.026 \times \text{feed rate} \times \text{current} - 0.153 \times \text{feed rate} \times \text{gap} - 3.0436E - 003 \times \text{dwell time} \times \text{current} + 3.502E - 003 \times \text{dwell time} \times \text{gap} - 0.015 \times \text{current} \times \text{gap} - 0.055 \times \text{feed rate2} - 4.271E - 003 \times \text{dwell time 2} + 0.011 \times \text{current2} - 0.059 * \text{gap 2} \quad ...(3)$$

The variables in the quadratic equation were coded to generate the response surface by limiting the responses into a domain of – 1 to + 1. Unstandardized equations can be used for predicting the responses.

Ramp function graph for rolled condition of the material for maximum mean effective case depth is shown in Fig.2. It gives the values of process parameters to obtain maximum value of mean effective case depth. The optimal value of mean effective case depth (3.09 mm) corresponds to feed rate = 2 mm/s, dwell time = 5 sec, current = 135 ampere and gap = 5.17 mm.

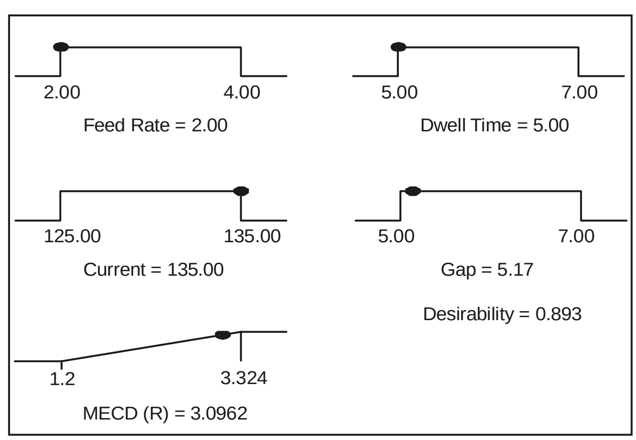

Fig.2. Ramp function graph as rolled condition of the material.

The desirability value of 0.893 corresponds to maximum value of mean effective case depth in the given range of parameters during rolled condition of the material. The normal probability plot of the residual is shown in Fig.3.

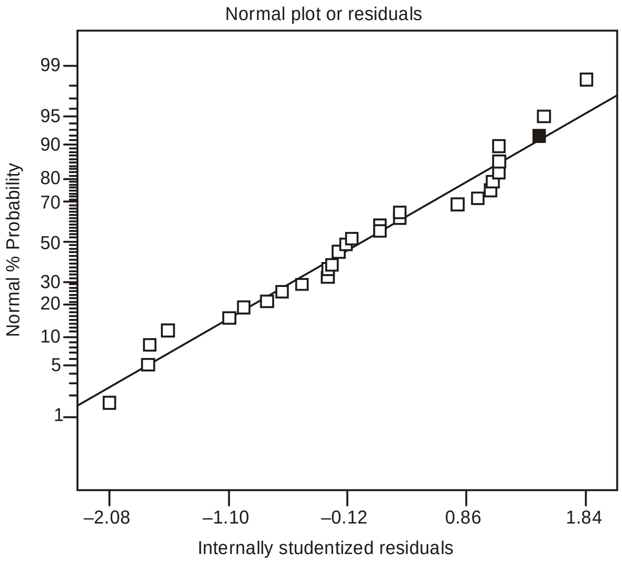

Fig.3. Normal probability curve of residuals as rolled condition of material.

A check on the plot in Fig.3 revealed that the residuals generally fall on the straight line which shows that the errors are distributed normally. In the same way the plot of the residuals versus the predicted response is shown in Fig.4.

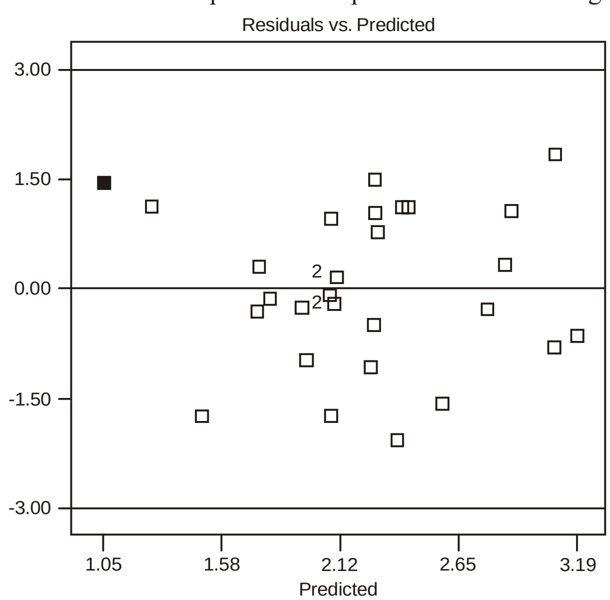

Fig.4. Plot of residual vs. predicted response.

It is revealed from the Fig.4 that there is no obvious pattern and it means that there is no reason to suspect any violation of the independence and finally the model proposed is adequate. The 3D surface graph and contours for the response are shown in Fig.5 and 6. The curvilinear profile in the figure is in accordance to the quadratic model fitted. It is clear from the Fig. that the optimum value of mean effective case depth is obtainable when the feed rate is somewhere at the middle of the range experimented. This is consistent with the fact that the parameter feed rate is most significant.

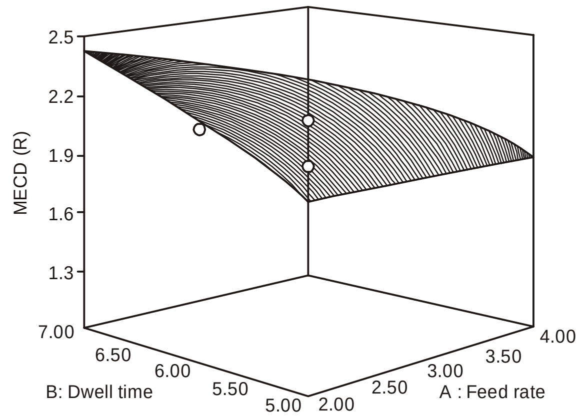

Fig.5. Surface graph during rolled condition of the material.

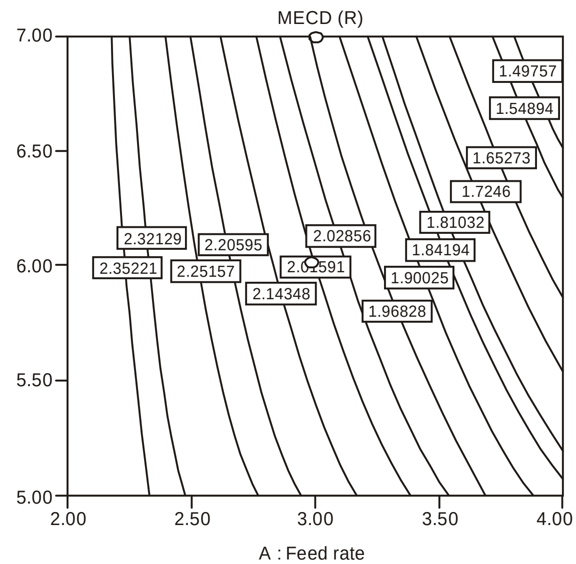

Fig.6. Contours during rolled condition of the material.

IV. CONCLUSIONS

The experimental investigation shows the effect of process parameters such as feed rate, dwell time, current, and gap between material and inductor coil, on the mean effective case depth of induction hardened AISI 1040 steel. The optimal value for mean effective case depth obtained was 3.09 mm in rolled condition of the material at feed rate of 2 mm/s, dwell time of 5 sec, current of 135 amperes and gap between material and inductor coil of 5.17 mm as optimum values of process parameters.

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