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Induction Hardening and Microstructure Analysis of Micro-Alloyed Steel Roller Shaft of an Undercarriage

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Abstract: The current work focuses on study of input parameters of induction hardening process of micro-alloyed steel roller shaft of an Undercarriage. Regression relation is generated for hardness using Response Surface Methodology (RSM) by using Design Expert Software as a tool for optimization. Further, the micro structure of selected shafts was analyzed.

Keywords–Induction hardening, Response Surface Methodology (RSM), Design Expert, central composite design

I. Introduction

Induction hardening is non-contact heat treatment process which is used to improve the hardness of a work piece. Heat treatment of steels has evolved in recent years as it deals with the problems and requirements of various sectors such as industrial, aerospace, automobile, infrastructure, locomotives and other sectors. In this paper response surface methodology (RSM) has been utilized for finding the optimal values of process parameters during induction hardening of Micro alloyed steel roller shaft which is used in undercarriages. Undercarriage is a supporting framework (or) structure for the body of a vehicle. It is defined as an assembly of various components, underneath the main body of the vehicle, which carries the load of the whole vehicle and assists its movement. Various process parameters, such as scan speed (speed at which the induction coil moves, which is measured in mm/sec), voltage, rotation and gap between the work piece and induction coil have been explored by experiments. Hardness has been considered as performance characteristic response. The experimentation was based on rotatable, central composite design (CCD) in response surface methodology. Microstructure and SEM (scanning electron microscope) analyses were also done for justification of work. The shaft material is Micro-alloyed steel is a type of alloy steel that contains small amounts of alloying elements, (0.05to0.15%) like-niobium, vanadium, titanium, molybdenum, zirconium, boron, and rare-earth metals. They are used to refine the grain microstructure or facilitate precipitation hardening. These steels lie, in terms of performance and cost, between carbon steel and low alloy steel. Yield strength is between 500 and 750 MPa (73,000 and 109,000 psi) without heat treatment.

II. Methodology

Response surface methodology (RSM) is a collection of experimental strategies, mathematical methods and statistical inference which enable an experimenter to make efficient empirical exploration of the system of interest. Many times these procedures are used to optimize a process. For example, we may wish to maximize yield of a chemical process by controlling temperature, pressure and amount of catalyst.

The basic strategy has four steps:

1. Procedures to move into the optimum region.
2. Behaviour of the response in the optimum region.
3. Estimation of the optimum conditions.
4. Verification.

The main objectives of RSM are:

- RSM is a collection of mathematical and statistical techniques that are useful for modelling and analysis in applications where a response of interest is influenced by several variables and the objective is to optimize the response.
- Optimize →maximize, minimize, or getting to a target.
- Or, where a nonlinear model is warranted when there is significant curvature in the response

Here, in this Experimentation, the outputs obtained are to be incorporated into the historical data of RSM in Design Experts Software and the optimum value of the outputs for the suggested model is to be obtained. Central Composite Design is the most popular response surface method (RSM) design is the central composite design (CCD).To summarize, central composite designs require 5 levels of each factor: -Alpha, -1, 0, 1, and +Alpha. One of the commendable attributes of the central composite design is that its structure lends itself to sequential experimentation. Central composite designs can be carried out in blocks. The value of alpha determines the location of the star points in a central composite design. It's expressed in terms of the coded values assigned to the low and high levels of the factors: -1 to +1. Alpha is usually somewhat larger than 1.

III. Experimentation

The experiment is conducted in an induction hardening machine. It is similar to that of traverse induction hardening but in this machine, the specimen (i.e., shaft) is also rotates about its vertical axis. The experimental apparatus consists of micro alloyed steel roller shafts, inductor coil of 65mm diameter and 75 mm, Induction hardening machine, safety gloves and shoes are the requirements for the induction heating purpose. After having the details of the number of trails to be conducted and the sufficient number of shafts, the induction hardening machine is set to conduct the experiment.

Since, the experiment is conducted in 2 sets for each inductor coil, the required number of shafts is double the number of trails resulted in the development of model. After ensuring the necessary safety precautions to be adopted, the experimentation is conducted by using the inductor coil of 65mm in the first set. A source of high frequency electricity has been used to drive a large alternating current through a copper coil. The passage of current through this coil generated a very intense and rapidly changing magnetic field in the space within the work coil. The work piece to be heated was placed within this intense alternating magnetic field where eddy currents were generated within the work piece and resistance lead to Joule heating of the metal. Each shaft is placed between the spindles and the combinations according to the trail are set in the Input program screen and the machine is switched on. While conducting the experiment, various observations such as heating time, cycle time and power consumed have been noted accordingly. In a similar procedure, the second set of experiment has been conducted by replacing the inductor coil with that of diameter 75mm.

Table 1- Process parameters and their working ranges

Process Parameters	Range	
	Minimum	Maximum
Scan-Speed (mm/sec)	8	20
Voltage (Volts)	50	92
Rotation (rpm)	50	99

After completion of the induction hardening, all the shafts were tested for surface hardness. Hardness at four different places was measured and the average was taken. The hardness was measured on a Rockwell hardness testing machine.

Table 2-Experimental parameters and hardness values

Trail	Scan Speed (mm/sec)	Voltage (volts)	Rotation (rpm)	Hardness (HRC)	
				65mm Ind. coil (1st set)	75mm Ind. coil (2nd set)
1	8	50	50	23.57	24.74
2	20	50	50	25.3	25.3
3	8	92	50	62.74	63.9
4	20	92	50	18.81	64.26
5	8	50	100	25.60	22.85
6	20	50	100	25.3	25.3
7	8	92	100	61.76	63.53
8	20	92	100	20.4	18.36
9	4	71	75	61.2	62.92
10	24	71	75	22.41	20.14
11	14	36	75	25.3	25.3
12	14	106	75	58.38	63.86
13	14	71	33	21.11	22.80
14	14	71	117	20.16	25.3
15	14	71	75	19.84	20.84
16	14	71	75	19.84	20.84
17	14	71	75	19.84	20.84
18	14	71	75	19.84	20.84
19	14	71	75	19.84	20.84
20	14	71	75	19.84	20.84

IV. Analysis:

In the analysis, the response data is entered in the Design expert software. Then the following steps are done in sequence to complete the analysis. The shafts with highest hardness in both the cases were selected and were analysed.

1. Transformation: Select response node and choose transformation.
2. Fit summary: Use this to evaluate models.
3. Model: choose model order and desired terms from list.
4. Analysis of variance (ANOVA): Analyze the chosen model and view results.
5. Diagnostics: Evaluate model and generate the regression equation.

The second part of the analysis is the study of the micro structure of the two shafts. Here the shafts were cut, the case depth was observed and then the shaft sectional area observed under the optical microscope.

1st set: With 65mm diameter inductor coil

Table 3 - Analysis tables for 1st set of trails

	Sequential	Adjusted	Predicted	
Source	p-value	R-Squared	R-Squared	
Linear	0.0061	0.4412	0.2133	
2FI	0.0794	0.5843	0.4417	
Quadratic	< 0.0001	0.9840	0.9354	Suggested
Cubic	0.4060	0.9851	-0.0383	Aliased

Table 4 - ANOVA tables for 1st set of trails

Response – Hardness					
Analysis of variance table [Partial sum of squares - Type III]					
	Sum of		Mean	F	p-value
Source	Squares	df	Square	Value	Prob> F
Model	5009.39	9	556.60	130.79	< 0.0001
A-scan speed	1627.74	1	1627.74	382.49	< 0.0001
B-voltage	1046.97	1	1046.97	246.02	< 0.0001
C-rotation	0.078	1	0.078	0.018	0.8948
AB	939.88	1	939.88	220.85	< 0.0001
AC	0.037	1	0.037	8.805E-003	0.9271
BC	0.25	1	0.25	0.059	0.8123
A^2	744.69	1	744.69	174.99	< 0.0001
B^2	747.07	1	747.07	175.55	< 0.0001
C^2	1.27	1	1.27	0.30	0.5965
Residual	42.56	10	4.26		
Lack of Fit	42.56	5	8.51		
Pure Error	0.000	5	0.000		
Cor Total	5051.95	19			

Table 5 - Percentage contribution of the factors:

Here, X1 – scan speed, X2 – voltage, X3 – rotation

Factor	% Contribution
x1	37.6197
x2	21.9005
x3	0.0368
x12	40.313
x13	00.00193
x23	0.0114
x123	0.1164

Final Equation in Terms of Actual Factors:	
hardness	=
+47.51135	
-1.33708	* scan speed
-0.67167	* voltage
+0.092004	* rotation
-0.086024	* scan speed * voltage
+4.56250E-004	* scan speed * rotation
-3.38690E-004	* voltage * rotation
+0.19968	* scan speed^2
+0.016326	* voltage^2
-4.75439E-004	* rotation^2

Table 6 - Solutions for 1st set of trails

S.No	scan speed (mm/sec)	Voltage (volts)	Rotation (rpm)	Hardness (HRC)
1	4.194	74.505	53.021	61.424
2	7.732	89.170	94.918	61.643
3	8.234	90.525	50.814	60.989
4	10.201	96.785	56.473	59.740
5	4.231	74.881	63.741	61.864
6	8.172	89.177	66.229	59.421
7	6.442	84.173	73.593	61.989
8	6.725	84.711	91.654	60.891
9	4.836	75.547	52.816	59.020

2nd set: with 75mm diameter inductor coil

Table 7 - Analysis tables for 2nd set of trails

	Sequential	Adjusted	Predicted	
Source	**p-value**	**R-Squared**	**R-Squared**	
Linear	0.0065	0.4371	0.2152	
2FI	0.2833	0.4777	-0.2108	
Quadratic	0.0029	0.8225	0.2226	Suggested
Cubic	< 0.0001	0.9977	0.8365	Aliased

Table 8 - ANOVA tables for 2nd set of trails

ANOVA for Response Surface Quadratic model					
Analysis of variance table [Partial sum of squares - Type III]					
Source	**Sum of Squares**	**dof**	**Mean Square**	**F Value**	**p-value Prob> F**
Model	5930.54	9	658.95	10.78	0.0005
A-scan speed	957.44	1	957.44	15.66	0.0027
B-voltage	2316.02	1	2316.02	37.89	0.0001
C-rotation	167.60	1	167.60	2.74	0.1288
AB	278.72	1	278.72	4.56	0.0585
AC	237.89	1	237.89	3.89	0.0768
BC	246.36	1	246.36	4.03	0.0725
A^2	826.77	1	826.77	13.52	0.0043
B^2	1065.86	1	1065.86	17.44	0.0019
C^2	14.04	1	14.04	0.23	0.6420
Residual	611.30	10	61.13		
Lack of Fit	611.30	5	122.26		
Pure Error	0.000	5	0.000		
Cor Total	6541.84	19			

Table 9 - Percentage contribution of the factors:

Here, x1 – scan speed, X2 – voltage, X3 – rotation

Factor	% Contribution
x1	6.9852
x2	50.0388
x3	09.3117
x12	9.135
x13	7.6418
x23	7.8814
x123	9.0055

Final Equation in Terms of Actual Factors:	
hardness	=
+14.22795	
-1.23402	* scan speed
-0.70044	* voltage
+0.88241	* rotation
-0.046845	* scan speed * voltage
-0.036354	* scan speed * rotation
-0.010570	* voltage * rotation
+0.21040	* scan speed^2
+0.019501	* voltage^2
+1.57941E-003	* rotation^2

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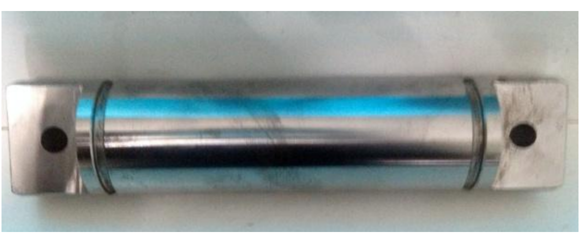
Table 10- Solutions for 2nd set of trails

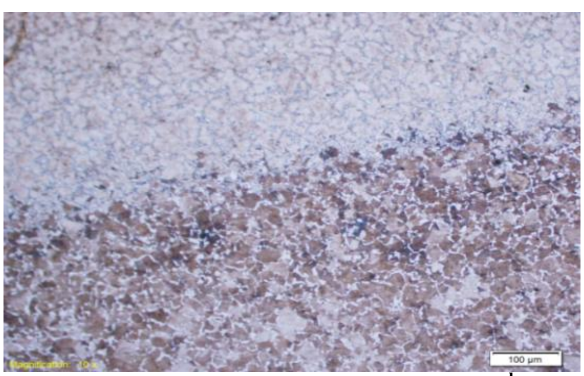
S.No	scan speed (mm/sec)	Voltage (volts)	Rotation (rpm)	Hardness (hrc)
1	11.782	98.447	70.293	61.177
2	8.467	88.733	53.267	60.188
3	8.349	89.035	63.564	59.349
4	10.743	96.360	70.776	60.972
5	10.428	98.889	97.442	59.552
6	8.525	91.620	84.425	59.760
7	14.348	98.990	62.382	58.437
8	10.482	98.870	89.359	61.261

Metallurgical Analysis:

Optical metallography, one of three general categories of metallography, which entails examination of materials using visible light to provide a magnified image of the micro- and macro-structure. It is applicable to studies ranging from fundamental research to production evaluations. The steps involved in metallographic analysis are selecting a sample, specimen preparation, sectioning, ground and polished so as to minimize disturbed or flawed surface metal caused by mechanical deformation, and thus to allow the true microstructure to be revealed by etching. In the present study the shaft specimens were etched using 2% Nitral solution [2 ml Nitric acid (AR grade) in 98 ml ethanol]. The etching of the shaft specimen was done for 5 seconds. After etching the specimens were observed inan Olympus optical microscope (Model:DP-72, Made in Japan). The shafts with highest hardness in both sets are taken as specimen and observed in microscope. The magnification used is 10X and 50X for both shafts.

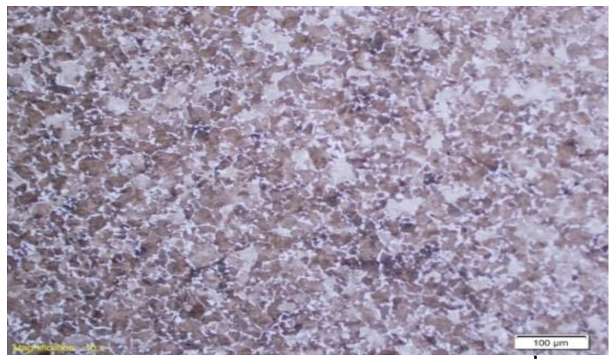


Micro alloyed steel roller shaft

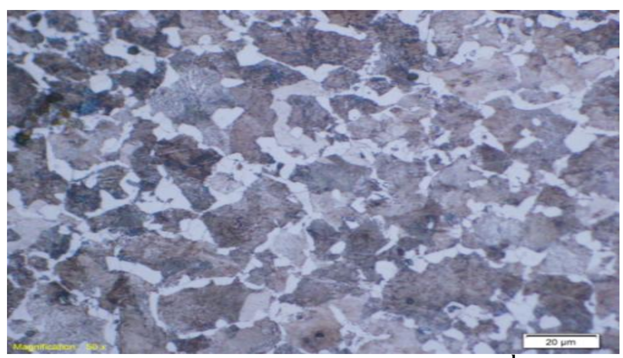


Microstructure of the interface region of 1st set specimen under 10X magnification

Microstructure of hardened region of 1st set specimen under 50X magnification



Microstructure of the interface region of 2nd set specimen under 10X magnification



Microstructure of hardened region of 2nd set specimen under 50X magnification

In the above figures, the light regions represent pearlite and ferrite and the dark regions represent martensite which is surrounded by light coloured boundary, which is consisting of pearlite and ferrite, the dark coloured region confirms the hardening of the material.

The case depth in case 1 was found observed to be 2.5mm and in case 2 as 4 mm. Hence, smaller inductor coli produced higher case depth in hardening of the shaft.

IV. CONCLUSION

To obtain hardness in the range of 58 to 62 hrc, the process parameters were observed during induction hardening and the conclusions made were as follows.

1. Scan speed of below 10mm/sec facilitated effective hardening of the shaft. But low scan speeds of below 8mm/sec took more cycle time to complete the process which affects the mass productivity, hence Scan speed in the range of 8 to 10 mm/sec is recommended.

2. High voltage in the order of more than 90-93 volts consumed very high power. At the same time, lower voltages couldn't provide efficient heating of the shaft and hence leading to non initiation of heating process. Hence voltage in the range of 90 to 95 volts is suggested.
3. Rotation speed in the range of 55 to 65 rpm along with the other parameters in the above said range resulted in better and efficient hardening.

The following are the conclusions derived from metallurgical analysis:

1. In the hardened region, complete martensitic phase was observed which confirms the hardening of the material.
2. The case depth was more in case of smaller inductor coil. Hence it was observed that, the distance between the coil and shaft influences the case hardening.
3. Decrease in hardness in few shafts is due to the presence of pearlite and ferrite at lower heating temperatures, which supports softening of the material. Hence heating temperature highly influenced the hardening process of the shaft.

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