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التحقيق التجريبي والتحسين للمعاملات العملية من خلال تصلب الحث باستخدام تصميم المعاملات من التجارب

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الخلاصة

التصلب الحثي هو عملية المعالجة الحرارية التي تستخدم لحالة انتقائية لتقوية سطح المادة التي توفر تحسين خصائص المادة. في هذه الورقة، يتم تقديم منهجية جديدة لتحسين الصلابة في الاتجاهات الطولية والعرضية على الجزء بأكمله، بدلا من منطقة انتقائية، بدون تشويه السطح. تجرى التجارب التجريبية على آلة التصلب الحثي المحمولة باستخدام نموذج تصميم معملية عشوائية تماما لتحليل العوامل الهامة. وقد استخدمت تقنية تحليل التباين (ANOVA) لدراسة تأثير العوامل (أي القدرة ووقت التسخين) وتفاعلها على الصلابة. كما تم إجراء الفحص المجهري الضوئي لمعرفة التغير في المراحل من خلال تغيير العوامل. وقد تم تطوير نموذج رياضي يربط بين الصلابة مع الطاقة ووقت التدفئة والذي يمكن استخدامه للتنبؤ بالاستجابة.

Experimental investigation and optimization of process parameters for through induction hardening using factorial design of experiments

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ABSTRACT

Induction hardening is a heat treating process that is used to selectively case hardens the surface of material providing improved material properties. In this paper, a novel methodology is introduced to optimize hardness in longitudinal & cross sectional directions over the entire part, instead of selective region, without deforming the surface. The experimental trials are conducted on portable induction hardening machine using completely randomized factorial design model to analyze significant factors. Analysis of variance (ANOVA) technique has been used to study the effect of factors (i.e., Power & Heating Time) & their interaction on Hardness. Optical microscopy has also been performed to find out the change in phases by varying the factors. A mathematical model relating hardness with power and heating time has been developed which can be used for response prediction.

INTRODUCTION

Induction hardening is widely employed in industries to temper the surfaces by hardening the components such as crank shafts, gears, bars, tubes, pipes, and joints. The purpose of hardening is to create a martensitic layer typically up to 0.25-2.3 mm on ferrous materials. This layer provides a hard and wear resistant surface with relatively soft and ductile core, which consequently increases the stiffness, torsional strength, and fatigue life of a component (Larson *et al*., 1987). The hardening process uses heating of materials above the upper critical temperature to modify the crystal structure form austenite and rapid cooling from that stage. With this arrangement, carbon can freely move to new locations. To keep carbon trapped at this new location, austenite is quenched, resulting in martensitic transformed structure.

The first application of induction hardening was recorded in the early 1920s by Midvale Steel Company, USA, to surface-harden the rollers of rolling mills. Later on, this technique became very popular in the automotive industries of the USA and Russia (Mühlbauer, 2008). The control over hardness thickness is a very complex study since the case depth depends on various factors. The exact model cannot be obtained through these parameters because of different nonlinearities associated with it. Available parameters in the literature are discussed in a subsequent literature review.

Kochure and Nandurker (2012) investigated the effects of heating power and time on hardness for optimized process parameters in induction hardening of EN8 D steel using Taguchi methodology. In that case study, a work piece of 19 mm diameter was selected to case-harden the surface for its use in automotive components such as axles, crank shafts, spline shafts, and gears. The optimal value of case depth at slot region was found to be 4 mm. The ANOVA and S/N ratio results confirmed that both variables, namely, power and heating time, have significant effect towards improved hardness.

Kohli and Singh (2010, 2012) optimized the mean effective case depth of induction hardened parts in rolled and normalized conditions using a response surface methodology. AISI 1040 steel was investigated under various process parameters including feed rate, current, time, and gap between the work piece and induction coil through experimentations using a central composite design. The optimum value for the case depth obtained was 3.09 mm. Palanivasan and Warkhedkar (2010) also investigated the variation in hardness and fatigue life of IC engine valve at different levels of power, heating time, and cooling media in the induction hardening process. The optimal case depth was found to be 1.5 mm.

Optimization of the induction hardened process of AISI 1040 steel with experimental design methods has been conducted by Onan *et al*. (2012). They initially studied the effects of three factors, namely, power supply, scan rate time, and distance between work piece and coil, on material properties. The Taguchi method using L27 experiment orthogonal arrays and analysis of variance (ANOVA) confirmed that the power ratio, scan rate time, and their interaction were more significant than the distance between work piece and coil. The effective case depth of induction hardened material optimally ended at 4.2 mm.

Kayacan and Colak (2004) used a fuzzy approach for induction hardening parameters selection. They selected power of heating, distance between coil and material, cooling time, and applied frequency as affecting parameters and concluded that the above parameters have direct effects on heating time and hardness thickness.

Various efforts have been reported for optimization of surface hardness using induction hardening process up to few millimeters, as outlined above. However, the study needs to be conducted for optimizing hardness along the entire surface in longitudinal as well as cross-sectional directions. This research involves experimental study, determination of significant process parameters through ANOVA, and verification through microscopic analysis. Two factors, heating power and heating time, have been chosen to investigate their individual and interaction effects on material hardness. Four levels of heating power and three of heating time have been selected. Completely randomized factorial experimental design has been selected to run the experiments and obtain the responses. ANOVA has been employed to compare the variation between treatments and variation within the treatments of the experimentally obtained values of response and to find significant factor(s) affecting the response. A regression model is also developed relating hardness with heating power and time.

EXPERIMENTAL WORK

The experimental work includes the selection of working material, experimental apparatus, and experimental plan, which determines the sequence and runs of the experiment.

Work piece and material specifications

The material selected for this process DIN 56NiCrMoV7 is used with composition of C 0.5-0.60 %, Si 0.10-0.40 %, Mn 0.65-0.95 %, P Max 0.03 %, S Max 0.03 %, Cr 1.00-1.20 %, Ni 1.50-1.80 %, Mo 0.45-0.55 %, and V 0.07-0.12 %. This material (Todic *et al*., 2012) can be used for various special purposes in automobile industry especially in crank pins, pistons pins, small shafts, and different connectivity components of mechanical assemblies. The work piece is 12 mm in diameter and 100 mm in length.

Experimental apparatus

The portable induction hardening machine with induction frequencies range of 10-50 kHz has been employed to perform all the experiments. Alternating current was passed through helical shaped water cooled copper coils. The work pieces were placed inside the coil where the magnetic field was induced and the work pieces were heated. This process was performed to affect the material from case to core; high values of process parameters were selected to achieve homogenized hardness throughout the work piece.

Experimental plan

Potential design factors are usually chosen through experience or literature review. The levels, over which the factor(s) will be varied, are then decided based upon the operating window.

Factors involving heating power and heating time, at four and three levels, respectively, have been selected as shown in Table 1. Factorial experimental design technique has been used to design the runs and collect the data. In factorial design, all possible treatment combinations of the levels of factors *A* and *B* are investigated. Minitab has been used to analyze the data. Two replicates at twelve treatment combinations resulted in 24 observations. In order to avoid any systematic bias in the response values, experiments were performed in a randomized manner. The run order, experimental design, and the observed responses are presented in Table 2.

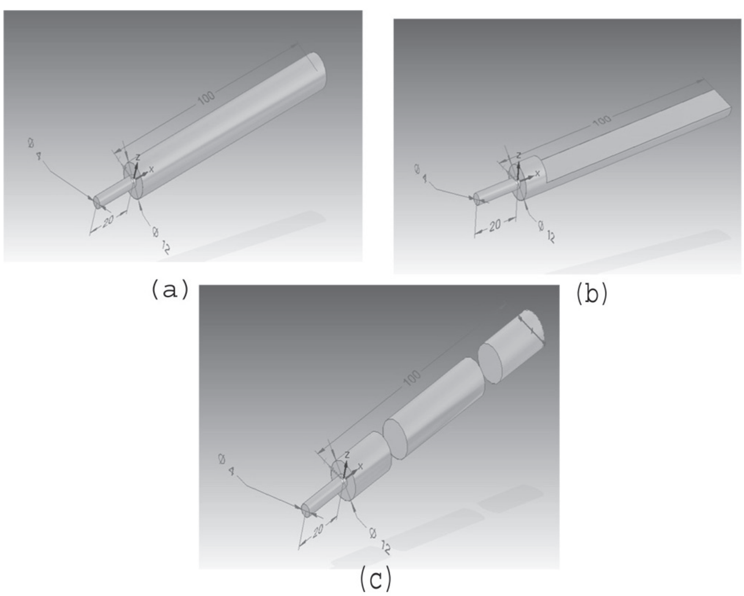


Figure 1. (a) Component model; (b) component longitudinal section; (c) component cross sections.

Table 1. Process parameters of factor levels.

Factors	Process Parameters	Level I	Level II	Level III	Level IV
A	Heating Power (kW)	10	15	20	25
B	Heating Time (Sec)	3	6	9	

A sample model is shown in Figure 1(a). To get the response in both directions, the samples were sectioned from the middle to record the reading longitudinally, as shown in Figure 1(b), whereas the samples were cut in three pieces to record the response in cross-sectional direction, as shown in Figure 1(c). Ten readings of response were taken at different locations on each sample, and the averages of hardness are shown in Table 2. The samples were collected from the same batch. The samples were sectioned using wire cutting technique, and hardness was measured on Rockwell Hardness Testing Machine [Wilson Wolpert] on C scale.

RESULTS AND DISCUSSIONS

Analysis of variance (ANOVA) technique was used to investigate the main effects and interactions, which have significant effects on the response. Tables 3 and 4 show the ANOVA for hardness in longitudinal and cross-sectional directions, respectively, where DF represents the degree of freedom and SS represent the sum of squares of variability in results. Mean of square (MS) is calculated by dividing SS with appropriate DF. F value, which is the ratio of MS of the parameters in question to MS of error, is used to determine the significance of parameters (Montgomery, 2010; Maji & Pratihar, 2011; Kehoe *et al*., 2011). The value of α, level of significance, is selected as 5%. High values of F and P values less than 0.05 indicate significant factors. From Tables 3 and 4, it is evident that the induction power, heating time, and their interaction significantly affect hardness in both directions.

Main effects of each parameter in both directions are represented in Figures 2(a) and 3(a). Figure 2(a) shows that the maximum hardness in longitudinal direction is achieved at 20 kW and 9 seconds, whereas the maximum performance in the cross-sectional direction is achieved at 20 kW and 6 seconds as shown in Figure 3(a). From the interactions plot in Figure 2(b), the maximum hardness is achieved at 20 kW and 6 seconds. Since the interaction is significant, it has more weightage than main effects plot, and thus power and time should be at 20 kW and 6 seconds for higher values of hardness in longitudinal direction. In Figure 3(b), it is evident from the interaction plot of power and time that the maximum hardness is achieved at 20 kW and 6 seconds in cross-sectional direction, which is the same as illustrated by the main effects plots in Figure 3(a).

Table 2. DOE factorial design table and response values.

Run order no.	Power (kW)	Time (Sec)	Hardness (longitudinally) HRC	Hardness (cross-sectionally) HRC	Means hardness HRC
10	10	3	46	46	46.0
2	10	6	48	49	48.5
13	10	9	50	51	50.5
14	15	3	48	53	50.5
6	15	6	58	58	58.0
11	15	9	61	56	58.5
5	20	3	57	60	58.5
1	20	6	60	61	60.5
8	20	9	57	58	57.5
4	25	3	48	44	46.0
3	25	6	55	58	56.5
7	25	9	60	60	60.0
24	10	3	47	46	46.5
15	10	6	48	50	49.0
21	10	9	50	50	50.0
19	15	3	48	52	50.0
18	15	6	59	58	58.5
20	15	9	58	57	57.5
9	20	3	57	59	58.0
23	20	6	60	59	59.5
12	20	9	56	58	57.0
16	25	3	46	44	45.0
17	25	6	56	58	57.0
22	25	9	57	60	58.5

It may be noted that while increasing the time and power, the hardness initially increases, but at higher power and time values, the samples will become deformed. As shown in Figure 9, the surface of the sample becomes ruptured at 20 kW and 9 seconds, and in Figure 10, the shape of the sample becomes deformed at 25 kW and time 9 seconds. Thus, the selected optimized process parameters are 20 kW power and 6 seconds for both directions. Secondly, the difference of hardness in both directions at a particular treatment combination of process parameters is marginal when compared with the mean values as shown in Table 2. This is also validated with surface contours obtained from Minitab as shown in Figures 4(a) and 4(b). If both plots are overlapped, higher values of hardness (57-60HRC) are obtained at almost similar values of power and time.

To support statistical results, optical microscopic analysis was performed to find out the changes in the phases of the metal during induction hardening. Microscopic analysis was performed on Metkon IMM 901 optical microscopic machine. Homogenization of austenite cannot be considered in induction hardening experiments because the time for each experiment is insufficient for the uniform distribution of carbon throughout the entire microstructure. Also it is uncertain whether critical temperatures have been reached or not. The knowledge of prior treatment is, therefore, necessary for analyzing microstructures. In this study, normalized samples were taken for induction hardening. The etchant used to etch this particular grade of samples is Lepara (Amar *et al*., 2003). For 10 kW power with heating time periods of 3, 6, and 9 seconds as shown in the micrographs of Figures 5(a), 5(b), and 5(c), the mean hardness values lies between 46 and 50.5 HRC. The corresponding microstructure at 100X shows darker areas, which is pearlite, whereas lighter areas show martensite. As temperature increases, lighter areas in the microstructure also increase, and hence the hardness values increase due to a larger volume fraction of the martensitic region as shown in the micrographs (Figures 5, 6, and 7). It is important to note here that the presence of ferrite in the microstructure cannot be overruled, but an increase in the hardness values favors the argument that martensite is dominant in lighter areas.

For 15 kW power at heating time 3 seconds, the hardness ranged between 50 and 50.5 HRC, but it increases to a value of 58.5 HRC for 9 seconds, as listed in Table 2. For 20 kW power, the interaction plot shows highest values of hardness for 6 seconds, which is contrary to the usual trend where hardness values were increasing with time. As per the trend, the maximum hardness is found for 25 kW power at 9 seconds test duration. However, this treatment combination is not selected because the sample undergoes deformation at these levels as shown in Figure 10. Therefore, the optimum values of parameters have been selected as 20 kW power with 6-second heating time duration.

Table 3. ANOVA table for hardness in longitudinal direction.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Power	3	302.167	302.167	100.722	92.97	0.000
Time	2	205.750	205.750	102.875	94.96	0.000
Power*time	6	125.583	125.583	20.931	19.32	0.000
Error	12	13.000	13.000	1.083		
Total	23	646.500				
S = 1.04083	R-Sq = 97.99%		R-Sq(adj) = 96.15%			

Table 4. ANOVA table for hardness in cross-sectional direction.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Power	3	344.125	344.125	114.708	305.89	0.000
Time	2	180.250	180.250	90.125	240.33	0.000
Power*time	6	182.750	182.750	30.458	81.22	0.000
Error	12	4.500	4.500	0.375		
Total	23	711.625				
S =0.612372	R-Sq = 99.37%		R-Sq(adj) = 98.79%			

Two regression equations have been obtained separately for the prediction of hardness in the longitudinal and cross-sectional directions represented by Equation (1) and Equation (2). These equations represent hardness as a function of power (P) and time (T) and are shown as follows:

$$\textit{Hardness-L} = 4.88 + 4.11\,P + 3.88\,T + 0.04\,P \times T - 0.113\,P^2 - 0.292\,T^2 \qquad (Eq.1)$$

$$\textit{Hardness-C} = 8.49 + 4.07\,P + 3.27\,T + 0.0967\,P \times T - 0.122\,P^2 - 0.333\,T^2 \qquad (Eq.2)$$

Regression equations with higher R^2, R^2 (adjusted) and appropriate Mallows-Cp values from the possible combination have been selected. To test the performance of the regression model, the absolute relative error is computed between the predicted and the experimental values (Al-Momani *et al*., 2012; Nguyen *et al*., 2014; Manimaran & Kumar, 2013). By putting the values of power and time for the most optimized process parameter, that is, 20 kW and 6 seconds, in Equations (1) and (2), the error was 0.92% in the longitudinal and 0.54% in cross-sectional directions. Hence, regression models are in great agreement in prediction compared with the experimental results.

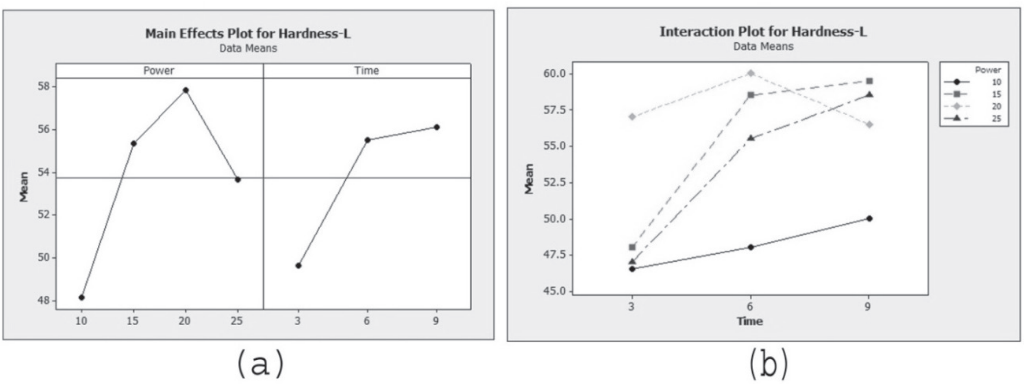


Figure 2. (a) Main effect plot of hardness in longitudinal direction;
(b) interaction plot of hardness in longitudinal direction.

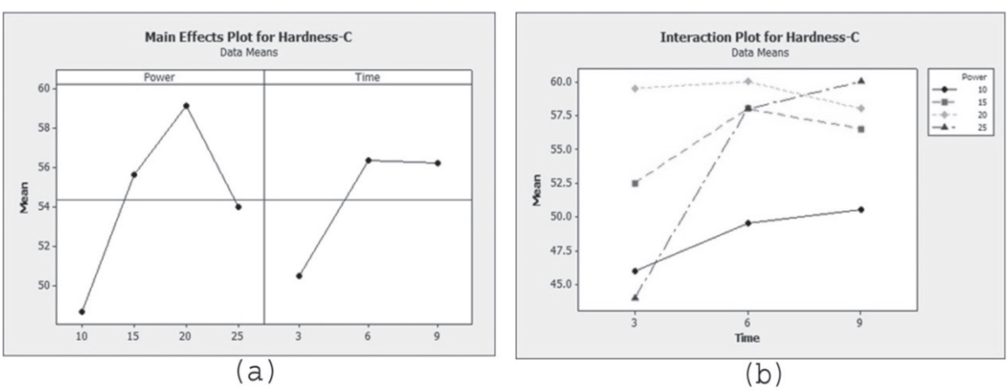
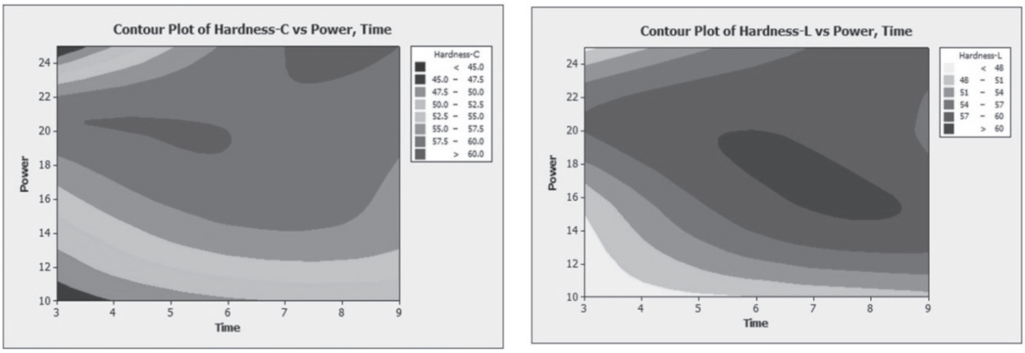
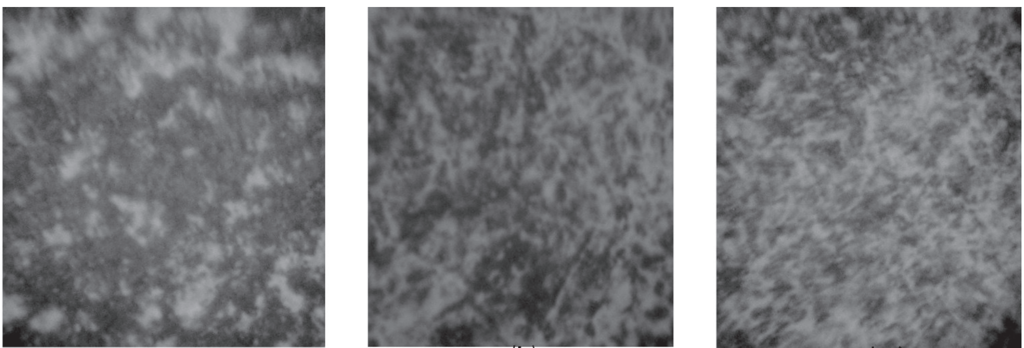


Figure 3. (a) Main effect plot of hardness in cross-sectional direction;
(b) interaction plot of hardness in cross-sectional direction.



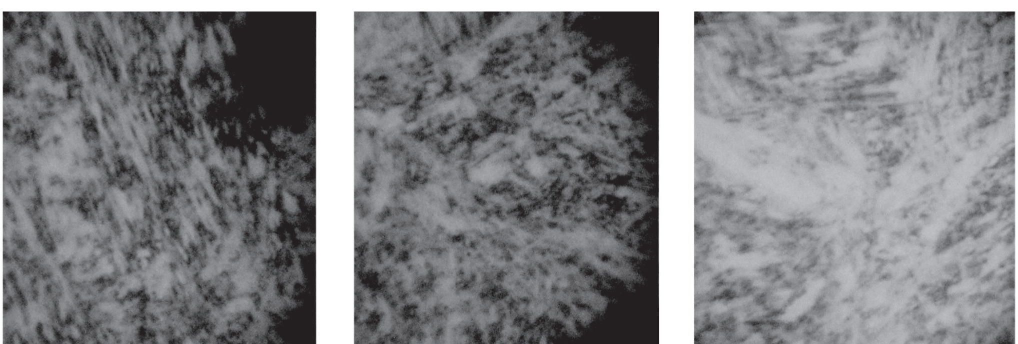
(a) (b)

Figure 4. (a) Surface contour plots of hardness in the cross-sectional direction; (b) surface contour plots of hardness in the longitudinal direction.



(a) (b) (c)

Figure 5. (a), (b), and (c) Optical micrographs (100X) at power 10kW and heating times 3, 6, and 9 seconds, respectively.



(a) (b) (c)

Figure 6. (a), (b), and (c) Optical micrographs (100X) at power 15kW and heating times 3, 6, and 9 seconds, respectively.

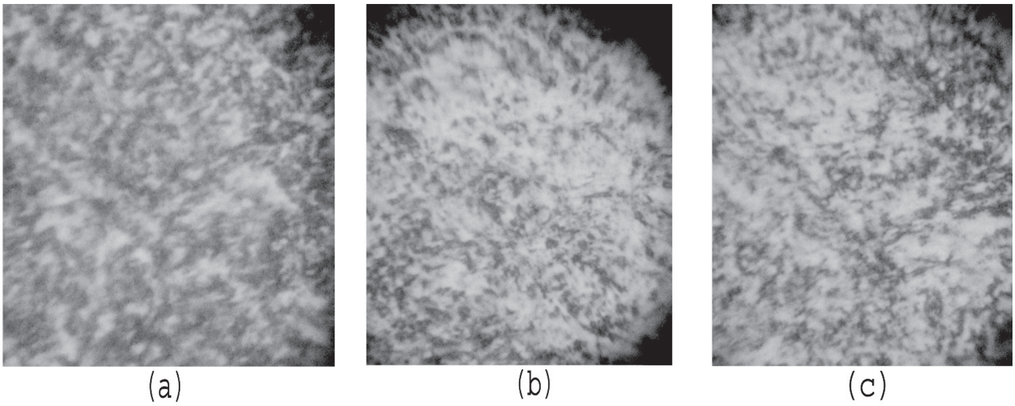


Figure 7. (a), (b), and (c) Optical micrographs (100X) at power 20kW and heating times 3, 6, and 9 seconds, respectively.

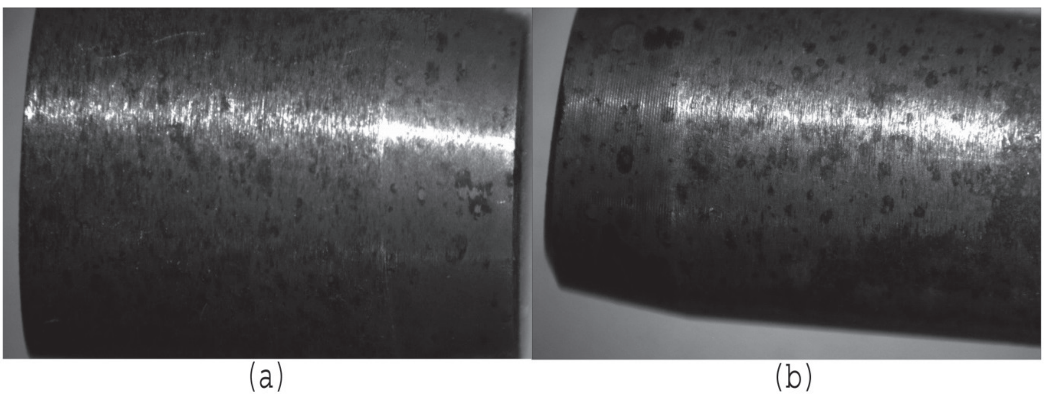


Figure 8. Stereo microscopic surface images of sample (10X) at power 20 kW and heating time 6 seconds.

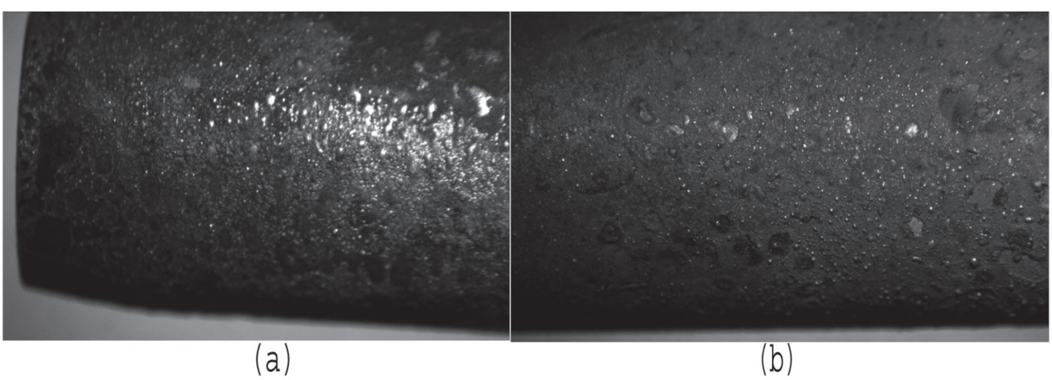


Figure 9. Stereo microscopic images of rupturing of sample surface (10X) at power 20 kW and heating time 9 seconds.

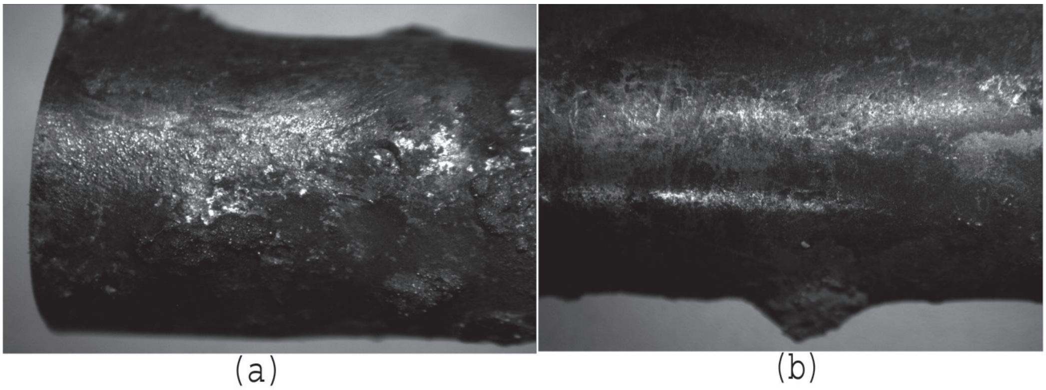


Figure 10. Stereo microscopic images of deformed sample surface (10X) at power 25 kW and heating time 9 seconds.

CONCLUSION

It is clear from this study that uniform hardness can be achieved by altering the process parameters, power and time. The maximum case depth of 12 mm is achieved through induction hardening process that was not recorded before. Multi-level factorial design has been used to design the experiments and ANOVA to find the process parameters having significant hardness of DIN 56NiCrMoV7 steel. The experimental results and ANOVA show that power and time have significant effect on hardness. Optimized hardness was found to be at 20 kW power and 6-second heating time for this case. Optical microscopic analysis confirmed the statistical results at optimum point through microscopic graphs of phases. The regression equation is in great agreement with the experimental results; it can be used to predict the hardness values at various combinations of power and time. In future, attempts may be made to model the induction hardening process through finite element analysis (FEA) and compare their results with the experiments.

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