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TURN-ASSISTED DEEP COLD ROLLING - A COST EFFECTIVE MECHANICAL SURFACE TREATMENT TECHNIQUE FOR SURFACE HARDNESS ENHANCEMENT

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ABSTRACT

In the present study, an optimization strategy based on desirability function approach together with response surface methodology has been used to optimize turn-aided deep cold rolling process of AISI 4140 steel. A regression model is developed to predict surface hardness. In the development of predictive model, rolling force, ball diameter, initial roughness of the workpiece, and number of tool passes are considered as model variables. The rolling force and ball diameter are found to be the significant factors on surface hardness. The predicted surface hardness values and the subsequent verification experiments under the optimal conditions confirmed the validity of the predicted model. The absolute average error between the experimental and predicted values at the optimal combination of parameter settings for surface hardness is calculated as 0.97%. Using the optimal processing parameters, the hardness is improved from 225 to 306 HV, which resulted in an increase in the near surface hardness by about 36%. The depth of compression is found to be more than 300 μm obtained from the microhardness measurements.

Keywords: *Turning, Deep Cold Rolling, Surface Hardness, Response Surface Methodology and Mechanical Surface Treatment*

1. Introduction

Surface modifications and surface treatments play a vital role in enhancing the service life of many critical parts that are used for engineering applications. Modern technologies employ advanced surface modification techniques, such as laser treatment and coatings to enhance the service life of components. However, most of these advanced technologies are expensive and economically unviable for simple to moderate critical applications such as those for automobiles and machine parts [1]. Numerous past studies have indicated that post-machining and metal-finishing operations have become attractive. One such process is 'deep cold rolling' which improves surface characteristics by plastically deforming the surface layers. In deep cold rolling process, the metal on the surface of the workpiece is redistributed without material loss. Besides producing a good surface finish, the deep cold rolling process has additional advantages such as securing increased hardness, corrosion resistance and fatigue life as a result of the produced residual compressive stress [2-5].

Deep Cold Rolling (DCR) is a surface treatment technique which is performed using a roller or ball type instrument to produce surface residual compressive stress to improve the fatigue life of materials and engineering components [6-8]. This method must be distinguished from roller burnishing where the main objective is to obtain a high quality surface. As a result of the contact of a ball with the surface of a component, a longitudinal groove is created which is accompanied by a plastic region followed by an elastic zone. Upon the separation of ball, the recovery of elastic zone creates a large compressive residual stress on the surface. A number of parameters can severely influence the deep cold rolling process and consequently the near surface residual stress among which the rolling force is proved to be the most important [9-11]. The increase in deep cold rolling force will increase the plastic deformation, as the penetration of the ball is increased [12]. This will lead to an increase in the internal compressive residual stress, which in turn causes a considerable increase in the surface hardness.

The literature review indicates that earlier investigations on deep cold rolling process are dealing primarily with microstructure, residual stress and fatigue life of specific materials like aluminium and titanium alloys. In these studies, specialized deep cold rolling set-ups are used with fatigue strength enhancement rather than analysis of resulting surface hardness. A study with an emphasis on optimization of DCR process

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for outcomes like fatigue life and hardness is readily not available.

This paper focusses on carrying out deep cold rolling process in a cost-effective way using the proposed turn-aided deep cold rolling instead of special machines and tools. The turn aided deep cold rolling (TADCR) proposed involves conventional lathe with a follower rest and rolling attachments, to improve surface properties of AISI 4140 steel. The objective of the work is to investigate the effect of process parameters in turn-aided deep cold rolling on surface hardness using central composite experimental design. The effect of four deep cold rolling parameters, namely, rolling force, ball diameter, initial roughness of the workpiece and number of passes are considered for investigation. An attempt is made to quantify the contribution of individual process parameters and develop a model to predict the surface hardness. Attempts are made to identify ranges of process parameters for optimum surface hardness. The optimum combinations of parameters are obtained by using both response surface methodology (RSM) and desirability function approach (DFA). This data could be an invaluable ready reckoner for the industry to select the optimum process parameters for required surface hardness. Validation experiments are conducted to verify the results for optimal conditions.

2. Experimental procedure

A DCR tool is designed, fabricated and used in the present work (see Figure 2). The DCR tool consists of two main parts, a shank and a collet to hold the ball. The ball is free to rotate with the rotation of the workpiece when in contact with the surface of the workpiece during DCR process. The ball could be removed easily from the tool for replacement, readjusting, or cleaning by opening the adapter (collet) and lock nut. Tungsten Carbide balls are used in the tool. The ball was loaded normal to the surface of a workpiece. As the ball rolls over the component, the pressure from the ball causes plastic deformation to occur on the surface of the material. Since the material develops resistance to deformation, work hardening takes place and a layer of residual compressive stress remains. The workpiece material used in this study is AISI 4140 steel. This steel is especially recommended for the manufacture of transmission shaft, gear shaft, crank shaft and also for a wide variety of automotive type applications [13]. The work pieces are received as bright cylindrical bars of 12mm diameter. The chemical composition of the material is shown in Table 1. The mechanical properties of the starting specimen at room temperature are shown in Table 2.

The specimens are prepared as per the ASTM-E466 requirements to conduct fatigue tests. Figure 1 shows the dimensions of the specimen that is used for conducting the experiments. Specimens are turned to given diameter on a conventional lathe to render a surface roughness common in turning process. The average initial hardness of the material measured by MATSUZAWA micro-vickers hardness tester and is found to be about 225HV.

The proposed turn-aided deep cold rolling (TADCR) set-up consists of a lathe (PSG type A 141) and an in-house custom designed tool and other accessories as shown in Figure 3. A Kistler dynamometer mounted on the lathe tool post is used to measure the forces during the process. The specimen is held in a three jaw chuck at one end and supported by tail stock at the other end. The rolling force is adjusted through depth of the rolling. The forces are recorded using the DynoWare software. An experimental plan with Central Composite Design (CCD) is used to investigate the influence of four parameters, rolling force, ball diameter, initial roughness of the workpiece and number of passes. Each parameter is considered in three levels. The parameters, their levels and magnitudes are shown in Table 3. Three replicates are used for each design point in the CCD.

Measurement of surface hardness is carried out for all samples. Then these samples, except one set, are subjected to TADCR process. Surface hardness is measured for these samples also. Samples are cut out along the feed direction and micro hardness variations across the depth of the specimen are recorded. Vickers indentor at 4.905N load and time 10 seconds is used to measure microhardness at consequent points spaced at 25µm. Average surface micro-hardness are determined from statistical samples of these values, size ranging from 5 - 15.

3. Results and discussions

Table 4 shows the results of 31 experiments that are performed based on central composite design. Three replicates are used with randomized run order for each parameter set. The last column shows the average surface hardness for each set of experiment.

The relative effect of each process parameter could be statistically studied by using analysis of variance (ANOVA). The ANOVA table for the surface hardness is given as Table 5. Results here indicate that ball diameter and rolling force are the two most significant parameters influencing the surface hardness

Table 1: Composition of Workpiece Material (wt. %)

Material	Composition										
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V
AISI 4140 (EN 19)	0.40	0.27	0.66	0.055	0.046	1.20	0.25	0.16	0.01	0.12	0.02

Table 2: Mechanical Properties of AISI 4140 Steel

Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Hardness (HV)
946	848	225

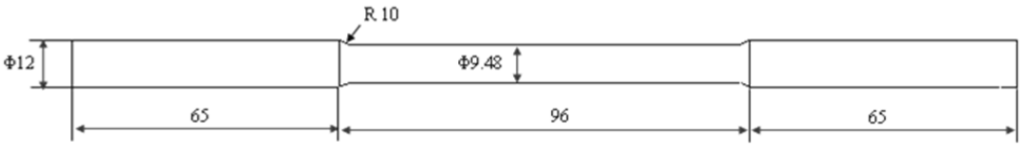
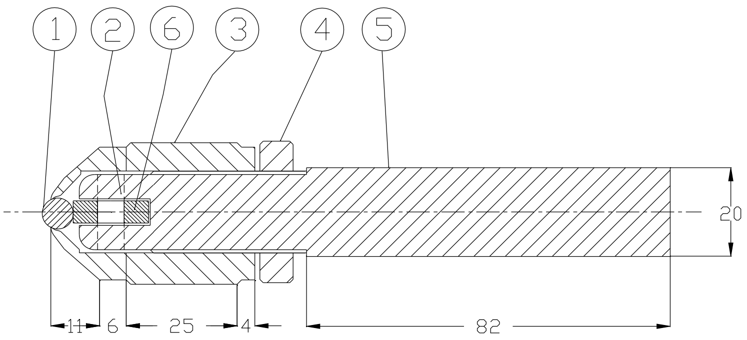


Fig. 1 Workpiece Geometry (mm)



1 - Ball, 2 - Hardened pin, 3 - Collet, 4 - Locking nut, 5 - Shank, 6 - Bearing

Figure 2: Deep cold rolling tool

Fig. 2 Deep Cold Rolling Tool

Fig. 3 Experimental Set-up of DCR Process

Table 3: Factors and levels for CCD

Symbol	Factor	Unit	Level 1	Level 2	Level 3
X_1	Ball Diameter	mm	6	8	10
X_2	Rolling Force	N	250	500	750
X_3	Initial Roughness	µm	4.84	6.15	7.46
X_4	No. of Passes		1	2	3

Table 4: CCD Matrix and Experimental Results

Exp. No.	Factors				Average Hardness (HV)
	X_1	X_2	X_3	X_4	
1	6	750	4.84	3	275.4
2	8	500	6.15	3	265.4
3	10	500	6.15	2	269.3
4	10	250	7.46	3	250.3
5	8	250	6.15	2	247.7
6	8	500	6.15	2	262.4
7	8	500	6.15	1	258.2
8	8	500	6.15	2	263.6
9	8	500	6.15	2	263.6
10	6	750	7.46	3	265.4
11	6	250	7.46	1	241.5
12	8	500	4.84	2	265.9
13	6	250	4.84	3	250.3
14	8	750	6.15	2	283.4
15	8	500	6.15	2	263.6
16	10	250	4.84	3	263.6
17	10	750	7.46	3	274.3
18	8	500	7.46	2	258.6
19	6	250	4.84	1	243.7
20	10	750	4.84	1	297.8
21	10	750	4.84	3	305.8
22	6	750	4.84	1	270.6
23	10	750	7.46	1	285.4
24	6	250	7.46	3	245.7
25	8	500	6.15	2	263.6
26	8	500	6.15	2	263.6
27	10	250	7.46	1	247.3
28	6	750	7.46	1	264.4
29	10	250	4.84	1	255
30	8	500	6.15	2	263.6
31	6	500	6.15	2	254.2

Table 5: The ANOVA Table for Surface Hardness

Source	DF	SS	MS	F	P	PC (%)
X_1	1	1051.88	107.101	16.17	0.001	16.29
X_2	1	4275.04	75.428	11.39	0.003	66.22
X_3	1	503.50	110.087	16.62	0.001	7.80
X_4	1	57.96	87.802	13.26	0.002	0.90
X_1X_2	1	172.27	172.266	26.01	0.000	2.67
X_1X_3	1	109.73	109.726	16.57	0.001	1.70
X_1X_4	1	4.10	4.101	0.62	0.441	0.06
X_2X_3	1	65.21	65.206	9.84	0.005	1.01
X_2X_4	1	24.26	24.256	3.66	0.070	0.38
X_3X_4	1	59.68	59.676	9.01	0.007	0.92
Residual Error	20	132.47	6.624			2.05
Total	30	6456.08				

*PC – percentage contribution

3.1 Empirical model for surface hardness

Experimental results are used to fit an empirical model. Regression analysis of values indicates a second order model could adequately represent the surface hardness variations. The regression equation can be thus expressed as in Eq. (1) in terms of coded factors.

The regression equation for hardness is given as,

$$HV = 154.826 + 7.194X_1 + 0.057X_2 + 9.989X_3 + 15.348X_4 + 0.007X_1X_2 - 1.000X_1X_3 - 0.253X_1X_4 - 0.006X_2X_3 - 0.005X_2X_4 - 1.474X_3X_4 \quad (1)$$

Where X_1, X_2, X_3, X_4 are the process parameters as shown in Table 3

The differences between measured and predicted responses are illustrated in Table 6. It could be observed here that predicted values of the surface hardness are close to those readings recorded experimentally with a confident level of 95%. In the prediction of surface hardness values the average absolute error for RSM is found to be as about 0.97%.

A measure of the model's overall performance denoted by R^2 is about 97.95% for surface hardness, which indicates that the fit is better. This is also indicated in the normal probability plot of the residuals as shown in Figure 4. The predicted values are found to be statistically close to the actual measured values. A check on the plot in Figure 4 shows that the residuals fall on a straight line implying that the errors are distributed normally. This scatter in the figure implies that the proposed model is adequate. It could be seen here that, the agreement between experimental surface hardness values and predicted surface hardness values is very good. The error for surface hardness values is found to be only about 0.97%.

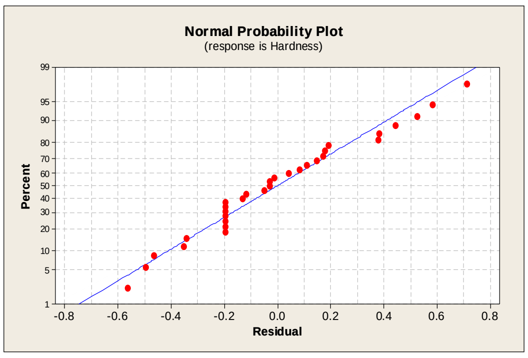


Fig. 4 Normal Probability Plot for Surface Hardness

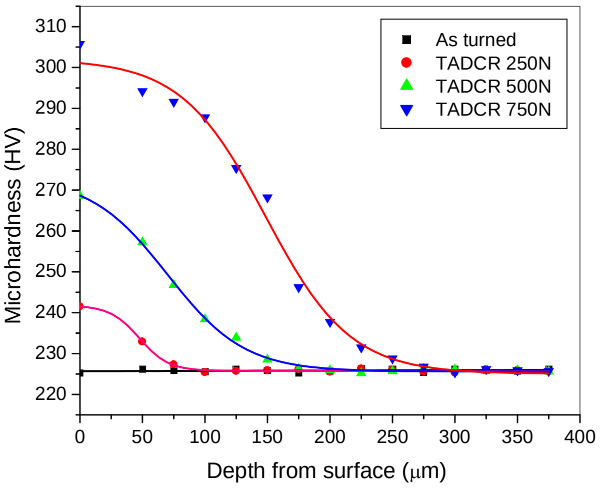


Fig. 5 Depth Profiles of Vickers Hardness for Turned and TADCR Samples

The subsurface microhardness obtained at different depth of the sample is plotted in Figure 5. The average microhardness of the as turned specimen is about 225 HV. Highest increase in hardness of about 306HV is achieved by using turn-aided deep cold rolling process for the force of 750N. The hardness is found to decrease with depth from the surface and eventually settles at hardness of original sample. For DCR with highest force variation could be seen upto a depth of about 300µm. From the same figure it could be observed that, surface microhardness of 175µm and 100µm under TADCR with 500N and 250N force respectively. This higher hardness at the surface and its progressive decrease is due to the amount of cold work experienced by the material manifesting into change in the grain shape/size.

3.2 Optimization of TADCR parameters for better surface hardness

Response surface optimization is done to determine how input parameters affect desirability of response (hardness). In this study, the target for the response is larger-the-better for surface hardness. Objective of this portion of the work is to achieve the desired surface hardness of the optimal turn aided deep cold rolling parameters. Response surface optimization, an ideal technique for determination of best processing parameter combination is used. Here, the goal is to maximize the hardness. An RSM optimization result for surface hardness is shown in Figure 6 and Table 7.

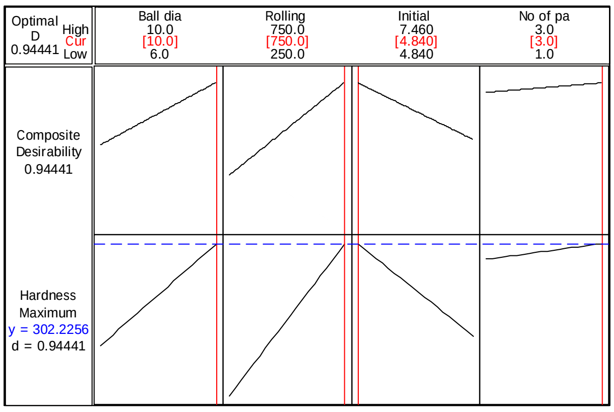


Fig. 6 Response Optimization Plot for Surface Hardness Parameter Components

Table 6: The Comparison between Measured and Predicted Surface Hardness

Exp. No	Surface Hardness (HV)		
	Measured	Predicted	% Error
1	275.4	278.6	1.16
2	265.4	267.9	0.96
3	269.3	274.3	1.84
4	250.3	249.0	0.54
5	247.7	249.7	0.79
6	262.4	266.2	1.44
7	258.2	264.4	2.41
8	263.6	266.2	0.98
9	263.6	266.2	0.98
10	265.4	265.7	0.11
11	241.5	242.9	0.58
12	265.9	271.4	2.06
13	250.3	251.1	0.33
14	283.4	282.7	0.25
15	263.6	266.2	0.98
16	263.6	264.5	0.34
17	274.3	282.6	3.02
18	258.6	261.0	0.92
19	243.7	240.2	1.42
20	297.8	302.1	1.45
21	305.8	306.0	0.06
22	270.6	272.7	0.78
23	285.4	286.4	0.36
24	245.7	246.1	0.15
25	263.6	266.2	0.98
26	263.6	266.2	0.98
27	247.3	247.8	0.21
28	264.4	267.5	1.18
29	255	255.6	0.25
30	263.6	266.2	0.98
31	254.2	258.1	1.54

Table 7: Optimum combination of parameters in response optimization for surface hardness

Parameters	Goal	Response	Optimum combination			
			Ball diameter (mm)	Rolling Force (N)	Initial Ra (µm)	No. of Pass
Hardness	Maximum	302.2HV	10	750	4.84	3

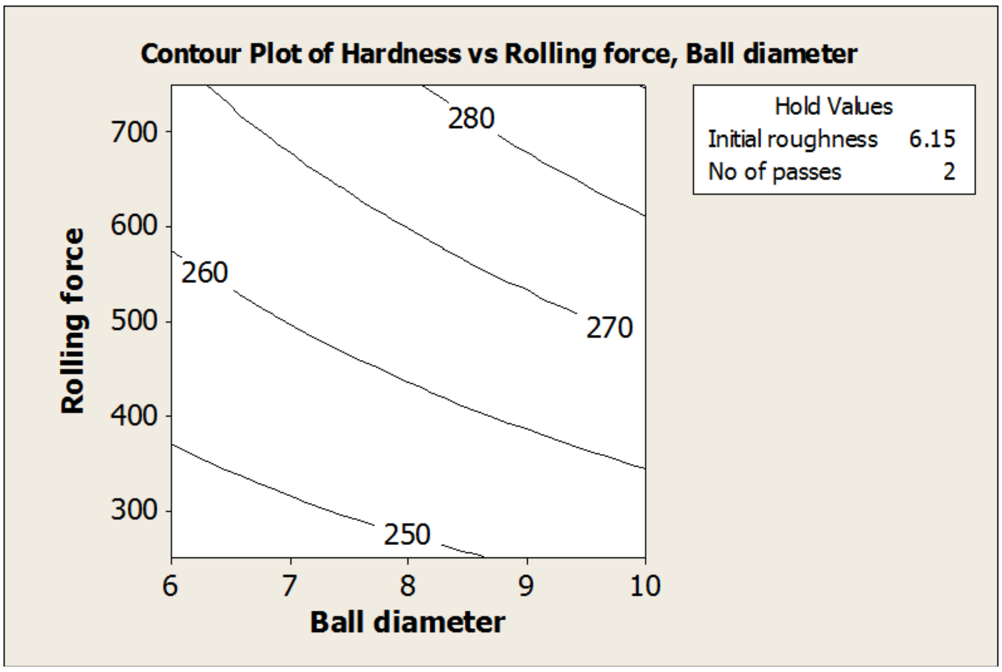


Fig. 7 Three Dimensional Plot of Surface Hardness

Table 8: Validation Experiments and Results

Parameters	Optimum combination				Measured	Predicted	% Error
	Ball diameter (mm)	Rolling Force (N)	Initial Ra (µm)	No. of Pass			
Hardness (HV)	10	750	4.84	3	306.5	306.0	0.16

The effect of ball diameter and rolling force on the surface hardness is represented in Figure 7. It could be observed here that the combination of large ball diameter and high rolling force results in a considerable surface hardness.

3.3 Validation experiments

The purpose of these experiments is to validate degree of agreement of the predictive model with experimental results. In this part of the study, after determining the optimum conditions, a set of experiments is conducted with identified optimum levels of the process parameters to verify the improvement in surface hardness. Results of validation experiments are shown in Table 8. The error between the experimental and predicted values at the optimal combination of parameter settings for surface hardness is only about 0.16%. This could establish the effectiveness of the response surface model for optimum deep cold rolling parameters.

4. Conclusions

In this study, the effects of four process parameters ball diameter, rolling force, initial roughness of the workpiece and number of tool passes are investigated by using different statistical techniques. Response surface methodology with central composite design is used to evaluate the effects of process parameters on the surface hardness of AISI 4140 steel. The factors significant to the surface hardness are ball diameter and rolling force. The empirical model developed and tested with experimental results of hardness indicates less significant errors amongst them. The error is about 0.97% only for surface hardness. After building the regression model, a numerical optimization technique using desirability function is employed to optimize the turn aided deep cold rolling process. The experimental results at the optimum process parameter combination confirm the effectiveness of the response surface models for optimum turn aided deep cold rolling process parameters. RSM approach can help manufacturers to determine the appropriate conditions, in order to achieve specific surface hardness.

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