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Analysis of Surface Hardness, Surface Roughness, and Near Surface Microstructure of AISI 4140 Steel Worked with Turn-Assisted Deep Cold Rolling Process

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Abstract**—**In the present study, response surface methodology has been used to optimize turn-assisted deep cold rolling process of AISI 4140 steel. A regression model is developed to predict surface hardness and surface roughness using response surface methodology and central composite design. In the development of predictive model, deep cold rolling force, ball diameter, initial roughness of the workpiece, and number of tool passes are considered as model variables. The rolling force and the ball diameter are the significant factors on the surface hardness and ball diameter and numbers of tool passes are found to be significant for surface roughness. The predicted surface hardness and surface roughness values and the subsequent verification experiments under the optimal operating 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 and surface roughness is calculated as 0.16% and 1.58% respectively. Using the optimal processing parameters, the surface hardness is improved from 225 to 306 HV, which resulted in an increase in the near surface hardness by about 36% and the surface roughness is improved from 4.84μm to 0.252 μm, which resulted in decrease in the surface roughness by about 95%. The depth of compression is found to be more than 300μm from the microstructure analysis and this is in correlation with the results obtained from the microhardness measurements. Taylor hobson talysurf tester, micro vickers hardness tester, optical microscopy and X-ray diffractometer are used to characterize the modified surface layer.

Keywords**—**Surface hardness, response surface methodology, microstructure, central composite design, deep cold rolling, surface roughness.

I. INTRODUCTION

IT is realized and witnessed over years that the life and the reliability of machine components or parts are affected greatly by the surface texture and thus the manufacturing technique adopted [1]. Thus varieties of surface enhancement techniques are developed to improve the condition of the surface and in turn life. The field of surface engineering has seen many developments that have improved the operating life and functionality of engineering components. From decades shot peening and roller burnishing have been extensively employed as secondary finishing processes to improve the workpiece surface quality and service life after primary machining process [2]. The introduction of near surface compressive residual stress during these processes is intended to extend the fatigue life and retain stability during applied service loading. Deep cold rolling (DCR) is a process capable of introducing much deeper residual compressive stresses and significant levels of cold work which could enhance the fatigue life, with surface hardness and surface finish as by products [3]. DCR is a surface treatment technique which is performed using a roller or ball type instrument to produce a surface residual compressive stress to enhance the fatigue life of engineering components. This method may be distinguished from shot peening and roller burnishing, where less force is imparted to create a thin residual compressive stress layer, and the main focus in these is quality of surface [4]. In all these processes, the impact/contact of a ball/roller with the surface of component creates a region of plastic strain followed by an elastic zone. Upon separation, the recovery of elastic zone induces compressive residual stress on the surface. The deep cold rolling process can induce deeper layer of compressive residual stress and thus is advantageous for better fatigue life of components coupled with additional benefits like better surface finish and hardness [5]. Thus, deep cold rolling is increasingly adopted as secondary process to enhance the surface finish, surface hardness, fatigue strength and thus the service lives of steel components used in automobile and aeronautical industry [6].

Large number of parameters could be influencing the deep cold rolling process and consequently the magnitude of near surface residual stress [2]. The parameters like ball diameter, rolling force, initial roughness of the workpiece and number of passes are deemed to be the most contributing among the parameters [7]. It is also revealed that lesser magnitude of rolling forces have no significant influence on the fatigue life and high magnitude ones may even aggravate it, by inducing micro cracks [8]. Thus optimizing the above process parameters to obtain an appropriate level of compressive residual stress coupled with good surface finish and hardness is a need of the hour.

The literature review shows 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 [9]. In these

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studies, specialized deep cold rolling set-ups are used for fatigue strength enhancement. Also a holistic study involving analysis of resulting surface roughness and hardness is not available. A study with emphasis on low cost DCR process with optimization for outcomes like fatigue life, surface roughness and hardness is most needed for small entrepreneurs presently.

Thus, this paper focusses on carrying out deep cold rolling process in a cost-effective way using the proposed turn-assisted deep cold rolling instead of special machines and tools. The turn-assisted deep cold rolling (TADCR) proposed involves conventional lathe with a follower rest and rolling attachments, to improve fatigue life and surface properties of AISI 4140 steel. The objective of the work is to investigate the effect of process parameters in turn-assisted deep cold rolling on surface roughness, hardness and residual compressive stress using central composite experimental design. The effect of four 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 and surface roughness. Attempts are made to identify ranges of process parameters for optimum residual stress, surface roughness and hardness. This data is developed to be an invaluable ready reckoner for a small entrepreneur to select the optimum process parameters for required residual compressive strength, surface hardness and finish. Validation experiments are conducted to verify the results for optimal conditions.

II. MATERIAL AND PROCESS

The workpiece material used in this study is AISI 4140 steel which is especially recommended for the manufacture of transmission shaft, gear shaft, crank shaft and also for a wide variety of automotive type applications [10]. The work pieces are received as bright cylindrical bars of 12mm diameter. The chemical composition of the material is shown in Table I. The mechanical properties of the starting specimen at room temperature are shown in Table II. The specimens are prepared as per the ASTM-E466 requirements to conduct fatigue tests. Fig. 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.

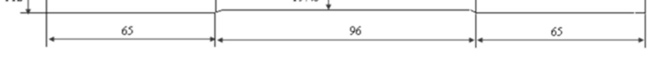


Fig. 1 Workpiece Geometry (mm)

TABLE I
COMPOSITION OF WORKPIECE MATERIAL (WT %)

Material	Composition							
	C	Si	Mn	P	S	Cr	Mo	Ni
AISI 4140	0.40	0.27	0.66	0.055	0.046	1.20	0.25	0.16

TABLE II
MECHANICAL PROPERTIES OF AISI 4140 STEEL

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

The proposed TADCR set-up consists of a lathe (PSG type A 141) and an in-house designed tool and other accessories as shown in Fig. 2. 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 III. Three replicates are used for each design point in the CCD.

Fig. 2 Experimental set-up of turn assisted deep cold rolling process

TABLE III
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

Measurement of the surface roughness, surface hardness and residual stress are carried out for all samples. Then these samples, except one set, are subjected to TADCR process. Surface hardness, surface roughness and residual stress are measured after TADCR as explained below. Samples are cut 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 micro-hardness at consequent points spaced at 25µm. Microstructure of the stressed region is acquired by an optical microscope. Surface roughness measurements are made using a Surtronic Taylor Hobson Talysurf tester and residual stress measurements are made by using a Rigaku X-ray diffractometer. Average surface roughness and surface micro-hardness are determined from statistical sample size of 5.

III. RESULTS AND DISCUSSION

Table IV shows the results of residual stress in samples subjected to turn-assisted deep cold rolling process. Residual compressive stress of turn-assisted deep cold rolled samples is much larger than that of the just turned sample. Gill et al. [3] reported that this increase in residual compressive stress is due to the cold working manifested as grain elongation. It is observed that TADCR process introduced substantial levels of residual compressive stresses at the specimen surface and in the near surface regions. It is apparent that after deep cold rolling, maximum residual compressive stress of 569MPa is measured immediately below the surface.

TABLE IV
RESIDUAL STRESS RESULTS OF TURNED AND TURN-ASSISTED DEEP COLD ROLLED SAMPLES

Sample	Residual stress (MPa)
As turned	93.83
DCR at 250N force	-292.93
DCR at 750N force	-568.74

TABLE V
CCD MATRIX AND EXPERIMENTAL RESULTS

Exp. No.	Factors				Average Surface Hardness (HV)	Average Surface roughness (µm)
	X_1	X_2	X_3	X_4		
1	6	750	4.84	3	275.4	0.335
2	8	500	6.15	3	265.4	0.339
3	10	500	6.15	2	269.3	0.391
4	10	250	7.46	3	250.3	0.328
5	8	250	6.15	2	247.7	0.486
6	8	500	6.15	2	262.4	0.399
7	8	500	6.15	1	258.2	0.503
8	8	500	6.15	2	263.6	0.400
9	8	500	6.15	2	263.6	0.399
10	6	750	7.46	3	265.4	0.326
11	6	250	7.46	1	241.5	0.618
12	8	500	4.84	2	265.9	0.392
13	6	250	4.84	3	250.3	0.428
14	8	750	6.15	2	283.4	0.391
15	8	500	6.15	2	263.6	0.394
16	10	250	4.84	3	263.6	0.269
17	10	750	7.46	3	274.3	0.371
18	8	500	7.46	2	258.6	0.411
19	6	250	4.84	1	243.7	0.690
20	10	750	4.84	1	297.8	0.466
21	10	750	4.84	3	305.8	0.261
22	6	750	4.84	1	270.6	0.569
23	10	750	7.46	1	285.4	0.596
24	6	250	7.46	3	245.7	0.373
25	8	500	6.15	2	263.6	0.398
26	8	500	6.15	2	263.6	0.395
27	10	250	7.46	1	247.3	0.494
28	6	750	7.46	1	264.4	0.584
29	10	250	4.84	1	255	0.451
30	8	500	6.15	2	263.6	0.396
31	6	500	6.15	2	254.2	0.460

TABLE VI
THE ANOVA TABLE FOR SURFACE ROUGHNESS

Source	DF	SS	MS	F	P	PC (%)
X_1	1	0.03175	0.03533	28.43	0.000	10.35
X_2	1	0.00341	0.01441	11.60	0.003	1.11
X_3	1	0.00366	0.01153	9.28	0.006	1.20
X_4	1	0.20930	0.00855	6.88	0.016	68.22
X_1X_2	1	0.01248	0.01248	10.05	0.005	4.07
X_1X_3	1	0.01339	0.01339	10.78	0.004	4.37
X_1X_4	1	0.00305	0.00305	2.46	0.133	1.00
X_2X_3	1	0.00459	0.00459	3.69	0.069	1.50
X_2X_4	1	0.00028	0.00028	0.23	0.640	0.09
X_3X_4	1	0.00000	0.00000	0.01	0.939	0.00
Res. Error	20	0.02485	0.00124			8.10
Total	30	0.30681				

PC – percentage contribution

TABLE VII
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
Res. Error	20	132.47	6.624			2.05
Total	30	6456.08				

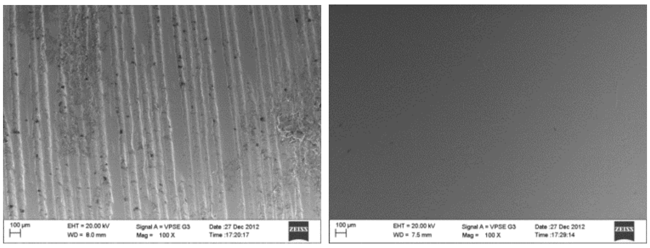
PC – percentage contribution

Table IV 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 two columns show the average surface hardness and surface roughness for each set of experiment.

The relative effect of each process parameter could be statistically studied by using analysis of variance (ANOVA). The ANOVA tables for the surface roughness and surface hardness are given as Tables VI and VII. Results here indicate that ball diameter and rolling force are the two most significant parameters influencing the surface hardness. Also interaction between these two parameters ball diameter and rolling force appear to be the most significant factors. Number of passes obviously is a parameter affecting the surface roughness with about 68.22% contribution.

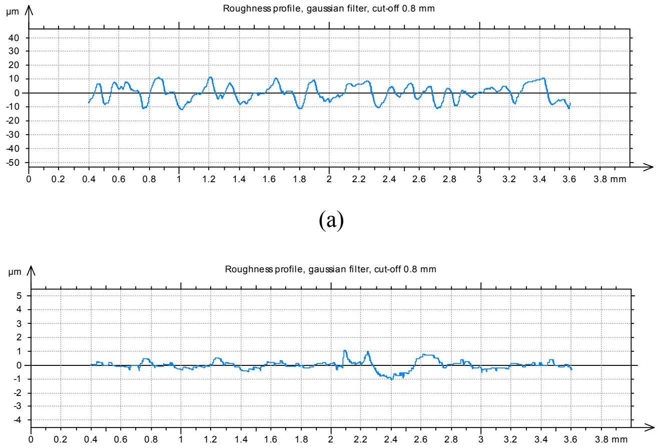
The surface roughness value decreases as the values of the number of passes vary from the lower to the higher level. The ball diameter has the maximum influence on the surface roughness at higher ball diameter. The surface texture deteriorates as the ball diameter decreases. At lower values of the ball diameter, powder like chips and small craters has been observed on the surface. The surface roughness increases as the surface has many minute undulations. Amongst the factors chosen, the rolling force and ball diameter has the maximum influence on surface hardness with 66.22% and 16.29% contribution. The hardness value increases as the rolling force vary from the lower to the higher level.

Fig. 3 shows surface pictures of turned and turn-assisted deep cold rolled specimen. A significant improvement of surface texture parameters is found and the pictures and profilograms show a very good surface condition of the turn-assisted deep cold rolled workpiece.



(a) (b)

Fig. 3 SEM images of the surface (a) after turning and (b) after turn-assisted deep cold rolling



(a)

(b)

Fig. 4 Roughness profile of the surface (a) before and (b) after turn assisted deep cold rolling

One of the roughness profiles obtained after turning is shown in Fig. 4 (a). The variations from the mean line are large, thus making the average value huge resulting in a high R_a value. Similarly, Fig. 4 (b) shows the roughness profile when all the parameters are kept at the optimum level. The variations from the mean line are small and thus the average values of the heights of the ordinates are small making the roughness value small.

The subsurface micro-hardness obtained at different depth of the sample is plotted in Fig. 5. The average micro-hardness of the as turned specimen is about 225 HV. Highest increase in hardness of about 306HV is achieved by using turn-assisted deep cold rolling process for the rolling force of 750N. The hardness is found to decrease with depth from the surface and eventually settles at hardness of original sample. For TADCR with highest force variation could be seen up to a depth of about 300μm (Fig. 5). From the same figure it could be observed that, surface micro-hardness 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. This could be visualized in the micrograph (Fig. 6).

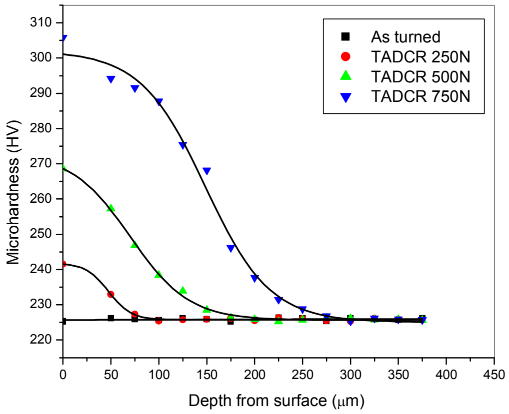
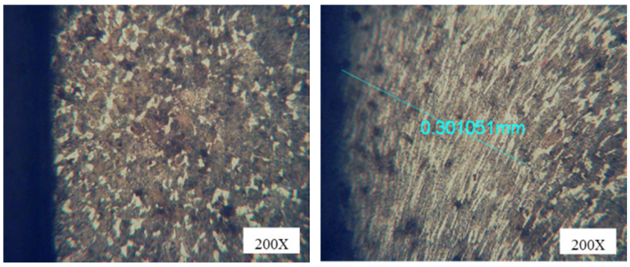


Fig. 5 Depth profiles of Vickers hardness for turned and TADCR samples



(a) (b)

Fig. 6 Microstructures of (a) turned and (b) TADCR sample at 750N force

Microstructure analysis under turned and turn-assisted deep cold rolled surfaces is carried out after polishing and etching (97% water + 3% nitric acid) using optical microscopy. The initial microstructure prior to turn-assisted deep cold rolling is shown in Fig. 6 (a). A representative microstructure beneath the turn-assisted deep cold rolled surface is presented in Fig. 6 (b), where grain deformations along the rolling direction can be noted. As the depth from the surface increases, the amount of ultrafine grain decreases. Since the strain induced by turn-assisted deep cold rolling decreases with distance from the surface to the bulk material, it is expected that the amount of ultrafine grains decreases with increasing depth. The increase in the rolling force increases the depth of the hardened layer. In this layer, there is a large distortion of the grains due to the plastic deformation accompanying the turn-assisted deep cold rolling process. As under the deep cold rolled surface the material is deeply strained, a blacker area than the base material could be seen for roughly 300μm from the top surface due to selective etching. This is in correlation with the results from the microhardness measurements.

A. Empirical Model for Surface Roughness and Surface Hardness

Experimental results are used to fit an empirical model. Regression analysis of values indicates a model could adequately represent the surface roughness and surface hardness variations. The regression equation can be thus expressed as in (1) and (2) in terms of coded factors.

The regression equation for surface roughness is given as,

$$R_a = 1.78449 - 0.13068X_1 - 0.00079X_2 - 0.10227X_3 - 0.15148X_4 + 0.00006X_1X_2 + 0.01104X_1X_3 + 0.00691X_1X_4 + 0.00005X_2X_3 - 0.00002X_2X_4 - 0.00052X_3X_4 \quad (1)$$

The regression equation for surface hardness is given as,

$$HV = 154.826 + 7.194X_1 + 0.057X_2 + 9.989X_3 + 15.348X_4 + 0.007X_1X_2 - 1.000X_1X_3 - 0.253X_1X_4 - 0.006X_2X_3 - 0.005X_2X_4 - 1.474X_3X_4 \quad (2)$$

where X_1, X_2, X_3, X_4 are the process parameters as shown in Table III

TABLE VIII
THE COMPARISON BETWEEN MEASURED AND PREDICTED SURFACE ROUGHNESS AND SURFACE HARDNESS

Exp No.	Surface Hardness (HV)			Surface Roughness (µm)		
	Measured	Predicted	% Error	Measured	Predicted	% Error
1	275.4	278.6	1.16	0.335	0.302	9.73
2	265.4	267.9	0.96	0.339	0.324	4.48
3	269.3	274.3	1.84	0.391	0.395	1.10
4	250.3	249.0	0.54	0.328	0.310	5.39
5	247.7	249.7	0.79	0.486	0.444	8.68
6	262.4	266.2	1.44	0.399	0.433	8.57
7	258.2	264.4	2.41	0.503	0.543	7.87
8	263.6	266.2	0.98	0.400	0.433	8.30
9	263.6	266.2	0.98	0.399	0.433	8.57
10	265.4	265.7	0.11	0.326	0.302	7.31
11	241.5	242.9	0.58	0.618	0.598	3.16
12	265.9	271.4	2.06	0.392	0.420	7.17
13	250.3	251.1	0.33	0.428	0.426	0.37
14	283.4	282.7	0.25	0.391	0.423	8.08
15	263.6	266.2	0.98	0.394	0.433	9.95
16	263.6	264.5	0.34	0.269	0.260	3.22
17	274.3	282.6	3.02	0.371	0.372	0.22
18	258.6	261.0	0.92	0.411	0.446	8.59
19	243.7	240.2	1.42	0.690	0.661	4.13
20	297.8	302.1	1.45	0.466	0.456	2.12
21	305.8	306.0	0.06	0.261	0.256	1.78
22	270.6	272.7	0.78	0.569	0.557	2.02
23	285.4	286.4	0.36	0.596	0.574	3.64
24	245.7	246.1	0.15	0.373	0.361	3.30
25	263.6	266.2	0.98	0.398	0.433	8.85
26	263.6	266.2	0.98	0.395	0.433	9.67
27	247.3	247.8	0.21	0.494	0.493	0.24
28	264.4	267.5	1.18	0.584	0.560	4.11
29	255	255.6	0.25	0.451	0.440	2.41
30	263.6	266.2	0.98	0.396	0.433	9.40
31	254.2	258.1	1.54	0.460	0.471	2.42

The model obtained could be used to predict the surface roughness (R_a) and surface hardness (HV) for all values of factors within the limits considered. The differences between measured and predicted responses are illustrated in Table VIII. It could be observed here that predicted values of the surface roughness and surface hardness are close to those readings recorded experimentally with a confident level of 95%.

A measure of the model's overall performance denoted by R^2 is about 91.9% for surface roughness and 97.95% for surface hardness, which indicates that the fit is better. It could be seen here that, the agreement between experimental surface roughness/hardness values and predicted surface roughness/hardness values is very good. The error for surface roughness and surface hardness values is found to be only about 5.31% and 0.97% respectively.

B. Optimization of TADCR Parameters for Lower Surface Roughness and Better Surface Hardness

Response surface optimization is done to determine how input parameters affect desirability of response (hardness and roughness). In this study, the target for the response is larger-the better for surface hardness and lower the better for surface roughness. Objective of this portion of the work is to achieve the desired surface roughness and hardness for optimal turn-assisted deep cold rolling parameters. Here, the goal is to maximize the surface hardness and minimize the surface roughness. RSM optimization results for surface roughness and hardness is shown in Fig. 7.

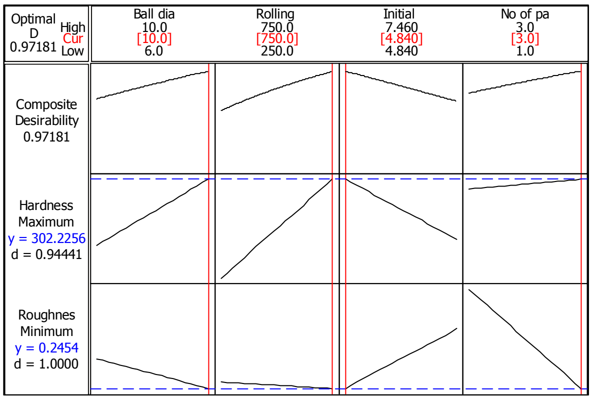
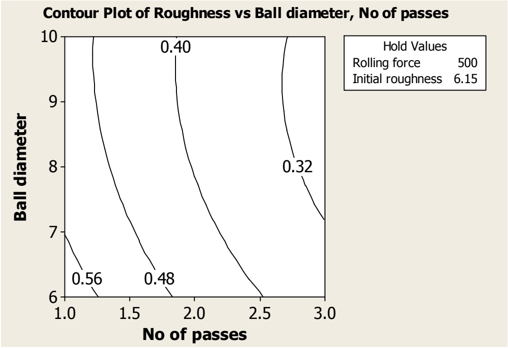


Fig. 7 Response optimization plot for surface roughness & hardness



(a)

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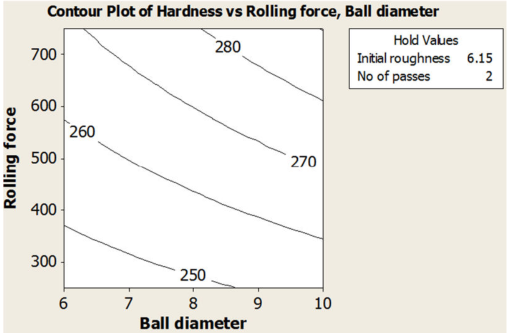

(b)

Fig. 8 Three dimensional plot of (a) surface roughness (b) surface hardness

The effect of ball diameter and number of tool passes on the surface roughness is represented in Fig. 8 (a). It could be observed here that the combination of large ball diameter and more number of tool passes results in a lower surface roughness. The effect of ball diameter and rolling force on the surface hardness is represented in Fig. 8 (b). It could be observed here that the combination of large ball diameter and high rolling force results in a considerable surface hardness.

C. 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 roughness and surface hardness. Results of validation experiments are shown in Table IX. The error between the experimental and predicted values at the optimal combination of parameter settings for surface roughness and surface hardness is only about 1.58% and 0.16% respectively. This could establish the effectiveness of the response surface model for optimum deep cold rolling parameters.

TABLE IX
VALIDATION EXPERIMENTS AND RESULTS

Parameters	Optimum combination				Measured	Predicted	% Error
	X_1	X_2	X_3	X_4			
Surface roughness (R_a)	10	750	4.84	3	0.252	0.256	1.58
Surface Hardness (HV)	10	750	4.84	3	306.5	306.0	0.16

IV. 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. Response surface methodology with central composite design is used to evaluate the effects of process parameters on the surface roughness and surface hardness of AISI 4140 steel. The factors significant to the surface roughness are obtained as ball diameter and number of tool passes and the factors significant to the surface hardness are ball diameter and rolling force. Experimental results showed that the microstructure and residual compressive stress can be significantly improved by increasing the rolling force. The empirical model developed and tested with experimental results of surface roughness and surface hardness indicates less significant errors amongst them. The error is only about 5.31% and 0.97% for surface roughness and surface hardness respectively. After building the regression model, a numerical optimization technique using RSM is employed to optimize the turn-assisted deep cold rolling process. The optimum process parameters found out are, ball diameter of 10mm, rolling force of 750N, initial roughness of 4.84µm and 3 number of passes. At the optimal processing parameters, the surface roughness is improved from 4.84µm to 0.252 µm, which resulted in decrease in the surface roughness by about 95% and the surface 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 300µm from the microstructure analysis and this is in correlation with the results obtained from the micro-hardness measurements. The experiments conducted at the optimum process parameter confirm the effectiveness of the response surface model for optimizing turn-assisted deep cold rolling process parameters.

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