Influence of deep cold rolling and low plasticity burnishing on surface hardness and surface roughness of AISI 4140 steel

P. R. Prabhu, S. M. Kulkarni, S. S. Sharma

***Abstract*—**Deep cold rolling (DCR) and low plasticity burnishing (LPB) process are cold working processes, which easily produce a smooth and work-hardened surface by plastic deformation of surface irregularities. The present study focuses on the surface roughness and surface hardness aspects of AISI 4140 work material, using fractional factorial design of experiments. The assessment of the surface integrity aspects on work material was done, in order to identify the predominant factors amongst the selected parameters. They were then categorized in order of significance followed by setting the levels of the factors for minimizing surface roughness and/or maximizing surface hardness. In the present work, the influence of main process parameters (force, feed rate, number of tool passes/overruns, initial roughness of the work piece, ball material, ball diameter and lubricant used) on the surface roughness and the hardness of AISI 4140 steel were studied for both LPB and DCR process and the results are compared. It was observed that by using LPB process surface hardness has been improved by 167% and in DCR process surface hardness has been improved by 442%. It was also found that the force, ball diameter, number of tool passes and initial roughness of the workpiece are the most pronounced parameters, which has a significant effect on the work piece's surface during deep cold rolling and low plasticity burnishing process.

***Keywords*—**Deep cold rolling, burnishing, surface roughness, surface hardness, design of experiments, AISI 4140 steel

I. INTRODUCTION

THE life and reliability of machine components or elements are affected greatly by the technological manufacturing and varieties of surface enhancement technologies applied and also by the sequence and conditions of their application. The field of surface engineering is highly respected and has demonstrated many developments that have improved the operational life of engineering components. A new field 'engineered surfaces' would be even more effective and economic route to successful manufacture [1]. Engineers who want to improve the life of a component will eventually have to take into consideration the surface of the component. Virtually all fatigue and corrosion-related failures originate from a surface produced by a manufacturing process. The ''integrity'' of the surface in resisting failure depends upon several characteristics including finish, residual stress, and cold working. Introduction of residual compressive stresses in metallic components has long been recognized to lead to enhanced fatigue strength. The compressive residual stresses must be retained in service for successful integration into structural design, and the process must be affordable and compatible with the manufacturing environment.

Deep cold rolling and low plasticity burnishing are two mechanical surface treatment methods that are increasingly used for enhancing the strength and endurance of metallic materials. These treatments can substantially increase resistance to wear and stress corrosion, and in particular enhance the fatigue strength. Near-surface compressive residual stresses and cold work are the predominant mechanisms for these effects, and can be related to a improved resistance to surface crack initiation and near-surface fatigue-crack growth [2]-[4]. Deep cold rolling (DCR) is commonly used for components that are rotationally symmetric (e.g., shafts) and is especially useful in overcoming the highly detrimental effects of notches. Besides near surface compressive residuals stresses and cold work, DCR can also reduce the surface roughness [5]. Low plasticity burnishing (LPB), on the other hand, is not limited by component geometry. LPB is used primarily for refinement of surface finish [6]-[8]. Although surface hardening and improvements in fatigue life are noted, no quantitative assessments exist.

Low plasticity burnishing (LPB) was developed to produce a deep layer of high compression, comparable to LSP, but with improved surface finish, lower cost, and minimal cold work [9]-[11]. The process is characterized by a single pass of a smooth free rolling spherical ball under a normal force just sufficient to deform the surface of the material in tension, creating a compressive layer of residual stress. The process is shown schematically in Figure 1. The ball is supported in a spherical fluid bearing with sufficient pressure to lift the ball off of the surface of the retaining spherical socket. The ball is in solid contact only with the surface to be burnished, and is free to roll in any direction on the surface of the work piece. Surface damage caused by sliding of the tool in conventional burnishing is virtually eliminated. The normal force, pressure,

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and tool position are computer controlled in a multi-axis CNC machine tool.

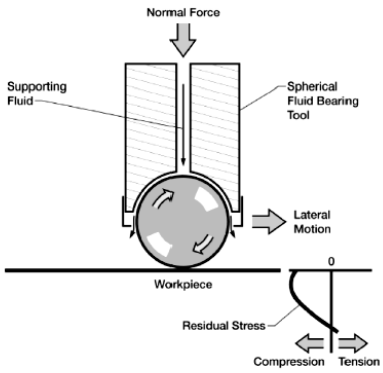

Fig. 1 Schematic diagram of LPB process [12]

“Deep cold rolling” also known as “Deep Rolling”, is very similar to LPB in terms of working principle. In DCR process, a ball is pressed against the part surface. When a load is applied on the ball, the force generates a high Hertzian compressive stress state in the material at its contact point. Therefore, a 3D stress situation appears when contacting the part surface, resulting in plastic deformation as soon as the yield point of material is exceeded. While tool and/or part are rotating, plastic deformation progresses continuously over the entire surface. It is fast, effective and inexpensive process. DCR can provide deeper and higher compressive residual stresses as compared to SP. It also produces smoother surfaces than SP. Work hardening (i.e. increase in surface micro-hardness) is another effect of DCR process. The achievement of three physical effects, namely the formation of compressive residual stresses, work hardening and achievement of quality surface finish, makes DCR one of the most effective and reliable techniques among the others.

II. Experimental Set-Up

The workpiece material used in this study is AISI 4140 steel. The chemical composition of which is presented in Table 1. The work pieces are received as cylindrical bright bars of 12mm diameter. Then the experimental specimens are prepared as shown in Figure 2 (As per ASTM standard E 466). Then, using the regular conditions for turning, moderate surface roughness is achieved, similar to that obtained in common manufacturing practices. The surface hardness of those specimens found to be 6C under Rockwell Hardness tester.

Fig. 2 Workpiece geometry (mm)

TABLE I
CHEMICAL COMPOSITION OF WORKPIECE MATERIAL (WT. %)

Material	Composition							
	C	Si	Mn	S	Cr	Mo	Ni	Cu
AISI 4140 (EN 19)	0.4	0.27	0.66	0.04	1.2	0.25	0.16	0.12

Fig. 3 Experimental set-up of DCR process

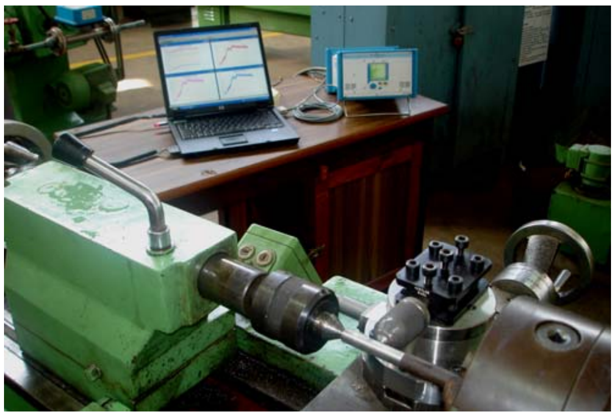

Fig. 4 Experimental set-up of LPB process

The set-up used in these tests consists of a lathe (PSG type A 141) for the processing of the specimens. Figures 3 and 4 show the complete set-up of DCR and LPB process. A 4 - component Kistler Dynamometer (piezoelectric transducer) was clamped on the lathe tool post to measure the forces during treatment. The signal generated by the piezoelectric transducer was first amplified by a charge amplifier and then connected to an A/D converter in the PC. The force was determined through processing using the DynoWare measuring force software.

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III. Experimental Procedure

Classical experimental design methods are complex and difficult to use [13], [14]. Furthermore, large numbers of experiments have to be carried out when number of parameters is large. In this study, the effect of several parameters on deep cold rolling and low plasticity burnishing process is determined efficiently by conducting fractional factorial experiments. To study the influence of various process parameters on the surface finish and hardness after DCR and LPB process seven parameters are chosen at 2 levels each as presented in Table 2. The only difference in the levels of experimentation when compared to DCR and LPB process is the force applied during the process. The force applied during LPB process is 100N and 200N where as for DCR process it is 250N and 750N.

Table 2 Factors and levels of experimentation

M1 – High Carbon High Chromium steel ball
M2 – Tungsten Carbide ball
L1 – Brake Oil
L2 – Gear Oil

Sl. No.	Factors	Levels	
		Low (-1)	High (1)
1 (A)	Ball material	M1	M2
2 (B)	Ball diameter (mm)	6	10
3 (C)	Feed (mm/min)	9	36
4 (D)	Rolling Force (N)	250	750
5 (E)	Initial R_a of work	4.84	7.46
6 (F)	Lubricant	L1	L2
7 (G)	Number of passes	1	3

IV. Results & Discussions

Rockwell hardness testing machine is used for hardness tests and a Surtronic Taylor Hobson Talysurf roughness tester for measuring the surface roughness of the treated samples. Surface roughness and surface hardness data are analyzed with the MINITAB 15 software.

A. Analysis of Deep cold rolling process:

The table below (Table 3) shows the mean surface roughness (MSR) and mean surface hardness (MSH) values for the different set of experiments.

Table III
Surface Roughness And Hardness Of AISI 4140 Steel Specimen After DCR Process

Resolution III Design									
Runs	A	B	C	D	E	F	G	MSR (μm)	MSH (HRC)
1	1	1	-1	1	-1	-1	-1	0.3925	30.25
2	1	1	1	1	1	1	1	0.47	25
3	-1	1	1	-1	-1	1	-1	0.205	28.5
4	1	-1	1	-1	1	-1	-1	0.27	24.75
5	1	1	-1	1	-1	-1	-1	0.13	24.25
6	-1	-1	-1	1	1	1	-1	0.3	24
7	-1	1	-1	-1	1	-1	1	1.635	26
8	-1	-1	1	1	-1	-1	1	0.2325	24.5
9	-1	-1	1	1	-1	-1	1	0.38	26.5
10	-1	1	1	-1	-1	1	-1	0.725	23.25
11	-1	-1	1	1	-1	-1	1	0.37	25.5
12	1	-1	-1	-1	-1	1	1	0.24	22
13	1	1	1	1	1	1	1	0.4425	25.75
14	1	1	-1	1	-1	-1	-1	0.515	32.5
15	1	-1	-1	-1	-1	1	1	0.85	20.25
16	-1	1	1	-1	-1	1	-1	1.125	27
17	-1	-1	-1	1	1	1	-1	0.98	20
18	-1	-1	-1	1	1	1	-1	0.4	22.25
19	1	-1	1	-1	1	-1	-1	0.335	24.25
20	1	1	1	1	1	1	1	0.445	26.5
21	-1	1	-1	-1	1	-1	1	0.335	23
22	1	-1	-1	-1	-1	1	1	0.335	27.25
23	1	-1	1	-1	1	-1	-1	0.69	28.25
24	-1	1	-1	-1	1	-1	1	0.88	26.5

1 - high level, -1 - low level

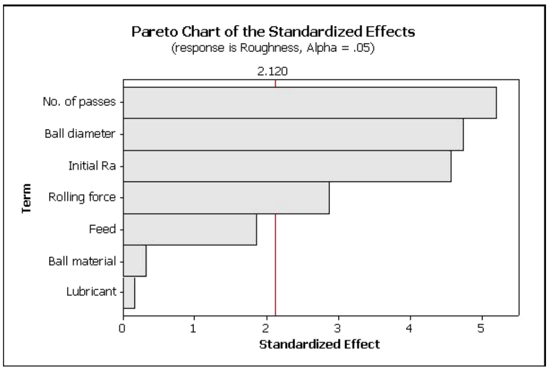

Fig. 5 Pareto chart for surface roughness

TABLE IV
FACTORIAL FIT: SURFACE ROUGHNESS VS PROCESS PARAMETERS

Term	Effect	Coef	SE Coef	T	P
Ball material	-0.0231	-0.0116	0.03467	-0.33	0.743
Ball diameter	-0.3294	-0.1647	0.03467	-4.75	0.000
Feed	-0.1290	-0.0645	0.03467	-1.86	0.081
Rolling force	0.1990	0.0995	0.03467	2.87	0.011
Initial Ra	0.3177	0.1589	0.03467	4.58	0.000
Lubricant	0.0106	0.0053	0.03467	0.15	0.880
No. of passes	-0.3610	-0.1805	0.03467	-5.21	0.000

P value < 0.05 has significant effect on surface roughness

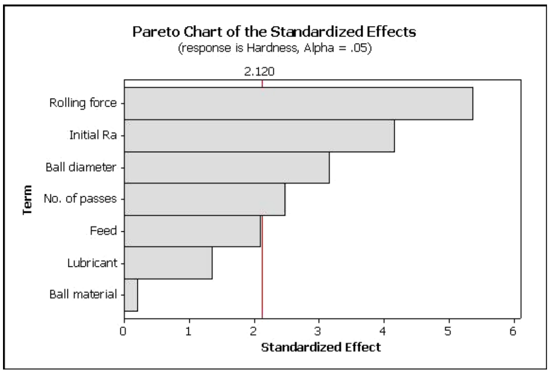

Fig. 6 Pareto chart for surface hardness

TABLE V
FACTORIAL FIT: SURFACE HARDNESS VS PROCESS PARAMETERS

Term	Effect	Coef	SE Coef	T	P
Ball material	0.125	0.062	0.3102	0.20	0.843
Ball diameter	1.958	0.979	0.3102	3.16	0.006
Feed	-1.292	-0.646	0.3102	-2.08	0.054
Rolling force	3.333	1.667	0.3102	5.37	0.000
Initial Ra	-2.583	-1.292	0.3102	-4.16	0.001
Lubricant	0.833	0.417	0.3102	1.34	0.198
No. of passes	-1.542	-0.771	0.3102	-2.48	0.024

Analysis of Variance surface roughness results as shown in Table 4 indicate that four process parameters - ball diameter, rolling force, initial surface roughness and number of tool passes are significant at 95% confidence level. The same can also be seen from the Pareto chart as shown in Fig. 5. ANOVA surface hardness results shown in Table 5 also indicates that the same four parameters ball diameter, rolling force, initial surface roughness and number of tool passes are significant at 95% confidence level. The same is observed from the Pareto chart as shown in Fig. 6.

The main effects plot in Figure 7 indicate that surface roughness improves with increase in ball diameter and increase in number of tool passes whereas surface roughness decreases with increase in rolling force and higher initial roughness of the workpiece. The main effects plot in Figure 8 indicates that surface hardness increases with increase in rolling force and increase in ball diameter whereas it decreases with increase in initial roughness of the workpiece and increase in number of tool passes.

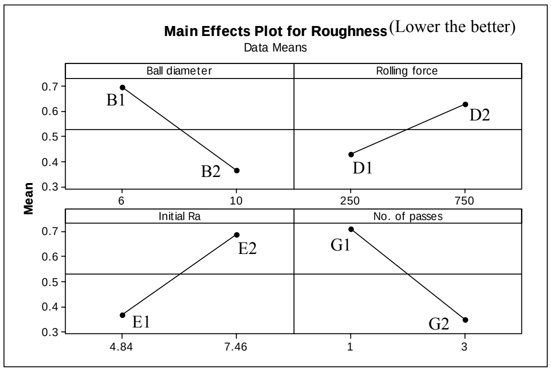

Fig. 7 Main effects plot of surface roughness for the significant factors

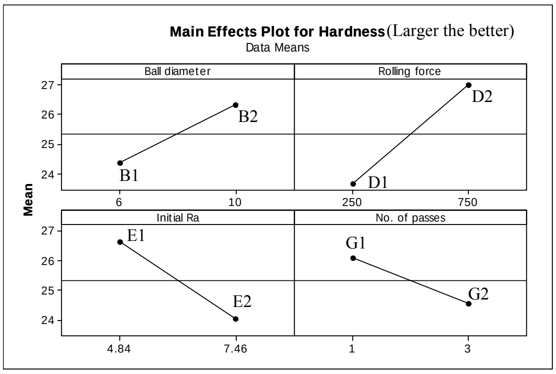

Fig. 8 Main effects plot of surface hardness for the significant factors

B. Analysis of Low plasticity burnishing process:

Table 6 shows the mean surface roughness (MSR) and mean surface hardness (MSH) values for different set of experiments.

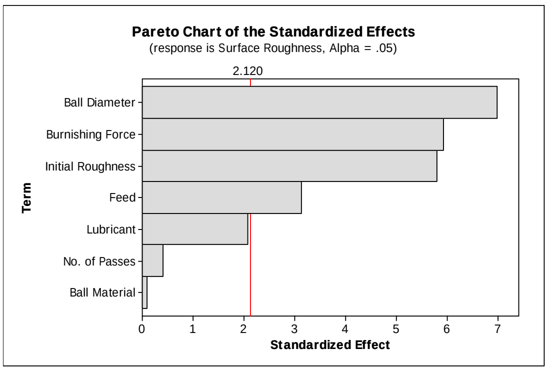

Fig. 9 Pareto chart for surface roughness

TABLE VI
SURFACE ROUGHNESS AND HARDNESS OF AISI 4140 STEEL SPECIMENS AFTER LPB PROCESS

	Resolution III Design								
Runs	A	B	C	D	E	F	G	MSR (μm)	MSH (HRC)
1	1	1	-1	1	-1	-1	-1	0.301	14
2	1	1	1	1	1	1	1	0.295	15
3	-1	1	1	-1	-1	1	-1	0.473	13
4	1	-1	1	-1	1	-1	-1	0.478	11
5	1	1	-1	1	-1	-1	-1	0.294	12
6	-1	-1	-1	1	1	1	-1	0.471	13
7	-1	1	-1	-1	1	-1	1	0.467	12
8	-1	-1	1	1	-1	-1	1	0.298	13
9	-1	-1	1	1	-1	-1	1	0.551	11
10	-1	1	1	-1	-1	1	-1	0.541	11
11	-1	-1	1	1	-1	-1	1	0.187	13
12	1	-1	-1	-1	-1	1	1	0.290	15
13	1	1	1	1	1	1	1	0.457	13
14	1	1	-1	1	-1	-1	-1	0.398	15
15	1	-1	-1	-1	-1	1	1	0.476	11
16	-1	1	1	-1	-1	1	-1	0.304	13
17	-1	-1	-1	1	1	1	-1	0.465	14
18	-1	-1	-1	1	1	1	-1	0.469	15
19	1	-1	1	-1	1	-1	-1	0.312	16
20	1	1	1	1	1	1	1	0.341	15
21	-1	1	-1	-1	1	-1	1	0.364	12
22	1	-1	-1	-1	-1	1	1	0.556	11
23	1	-1	1	-1	1	-1	-1	0.481	11
24	-1	1	-1	-1	1	-1	1	0.367	12

1 - high level, -1 - low level

TABLE VII
FACTORIAL FIT: SURFACE ROUGHNESS VS PROCESS PARAMETERS

Term	Effect	Coef	SE Coef	T	P
Ball material	0.00150	0.00075	0.008143	0.09	0.928
Ball diameter	-0.11383	-0.05692	0.008143	-6.99	0.000
Feed	-0.05083	-0.02542	0.008143	-3.12	0.007
Burnishing force	-0.09667	-0.04833	0.008143	-5.94	0.000
Initial Ra	0.09433	0.04717	0.008143	5.79	0.000
Lubricant	-0.03367	-0.01683	0.008143	-2.07	0.055
No. of passes	-0.00650	-0.00325	0.008143	-0.40	0.695

P value < 0.05 has significant effect on surface roughness

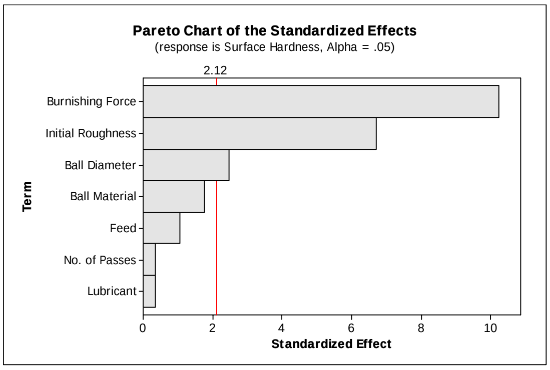

Fig. 10 Pareto chart for surface hardness

TABLE VIII
FACTORIAL FIT: SURFACE HARDNESS VS PROCESS PARAMETERS

Term	Effect	Coef	SE Coef	T	P
Ball material	-0.4167	-0.2083	0.1179	-1.77	0.096
Ball diameter	-0.5833	-0.2917	0.1179	-2.47	0.025
Feed	-0.2500	-0.1250	0.1179	-1.06	0.305
Burnishing force	2.4167	1.2083	0.1179	10.25	0.000
Initial Ra	-1.5833	-0.7917	0.1179	-6.72	0.000
Lubricant	-0.0833	-0.0417	0.1179	-0.35	0.728
No. of passes	-0.0833	-0.0417	0.1179	-0.35	0.728

P value < 0.05 has significant effect on surface roughness

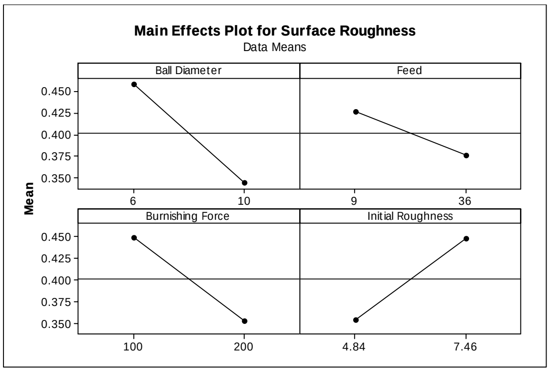

Fig. 11 Main effects plot of surface roughness for the significant factors

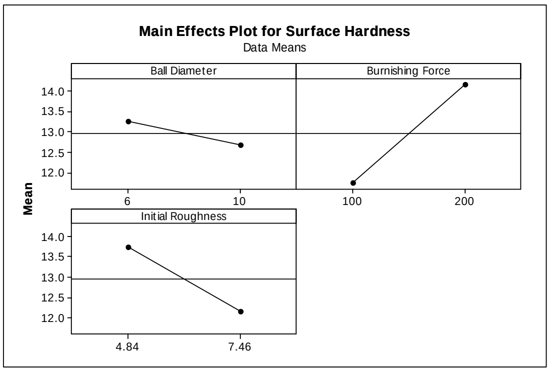

Fig. 12 Main effects plot of surface hardness for the significant factors

Analysis of Variance (ANOVA) surface roughness results as shown in Table 7 indicates that four process parameters - ball diameter, burnishing force, initial surface roughness and feed are significant at 95% confidence level. The same can also be seen from the Pareto chart as shown in Fig. 9. ANOVA surface hardness results shown in Table 8 also indicates that the same three parameters ball diameter, burnishing force and initial surface roughness of workpiece are significant at 95% confidence level. The same is observed from the Pareto chart as shown in Fig. 10.

The main effects plot in Figure 11 indicate that surface roughness improves with increase in ball diameter, increase in feed and increase in burnishing force whereas surface roughness decreases with increase in initial roughness of the workpiece. The main effects plot in Figure 12 indicates that surface hardness increases with increase in rolling force whereas it decreases with decrease in initial roughness of the workpiece and decrease in ball diameter.

V. Conclusion

Based on the above observations the following conclusions may be drawn.

- √ It is observed from the ANOVA table and main effects graphs that rolling force, ball diameter, initial roughness of the work piece, number of tool passes have a significant effect on the responses in DCR process.
- √ It is also observed from the ANOVA table and main effects graphs that, burnishing force, ball diameter and initial roughness of the work piece have a significant effect on the responses in LPB process.
- √ Using LPB process surface hardness has been improved by 167% and in DCR process surface hardness has been improved by 442%.
- √ The rolling force play an important role in enhancing the hardness of the treated specimens which inturn will have an influence in improving the fatigue life of the component. Higher the surface hardness higher will be the residual compressive stress, and thus higher the fatigue life of the component.
- √ From the experiments it is also inferred that ball material, feed and lubricant have very less influence on the response in both DCR and LPB process.

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