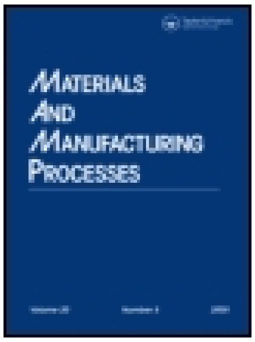

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Investigations on the Effect of Ball Burnishing Parameters on Surface Hardness and Wear Resistance of HSLA Dual-Phase Steels

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Surface finish has a vital influence on most functional properties of a component like fatigue life, wear resistance, corrosion resistance, etc. This has given birth to processes such as lapping, honing, burnishing, etc. Burnishing is a fine finishing operation involving the cold working plastic deformation of surface layers to enhance the surface integrity and the functional utility of a component. The present study has been carried out to establish the effect of burnishing parameters viz. feed rate, speed, force, ball diameter and lubricant on surface hardness, and wear resistance of HSLA dual-phase steel specimens. The result indicates that burnishing parameters have significant effect on the surface hardness and wear resistance.

Keywords Burnishing; Composite microstructures; Compressive residual stress; Double quenching; Dual phase; Factorial design; Fatigue resistance; Hardness; High-strength low alloy; Inter-Critical Temperature; Kinetics of formation; Opto mechanical; Tribology; Volume fraction; Work hardening.

1. Introduction

In present days, increased attention is being paid to surface integrity obtained, as surface finish is important not only on cosmetic grounds, but also because it affects the functional performance of the component and it is important for process control. Conventional processes have effects on surface finish, which causes the evaluation of processes like grinding, lapping, honing, burnishing, polishing, etc. In recent years, however, much attention has been focused on processes that improve surface characteristics by plastic deformation. Burnishing is such a process, which employs hard rollers and balls for the deformation. Besides improving the surface finish, burnishing secures increased hardness, wear resistance, corrosion resistance, and fatigue life. The process can be automated to increase the production rate. Ball burnishing is a nontraditional finishing method that employs a hardened ball to plastically deform a surface, and it shows much promise. The work hardening is associated with the plastic deformation and compressive nature of the stresses imposed, and improves the functional properties of the component.

The finishing of metals with a hardened surface layer has attracted the interest of researchers, e.g., those in the opto mechanical industry. The functional performance of a component, such as fatigue strength, load-bearing capacity, wear resistance, and corrosion resistance depends on its surface characteristics such as hardness, surface finish, induced residual stresses, and topography.

Luo and Liu [1] described burnishing as a cold working process that easily produces a smooth and work-hardened surface by plastic deformation of surface irregularities. In their work, the influence of the main burnishing parameters (speed, feed, force, number of tool passes, and ball diameter) on surface roughness and the hardness of two different nonferrous metals were studied. It was found that the burnishing force and the number of tool passes are the most pronounced parameters, which gave great effect on the surface finish of the work pieces during the burnishing process.

Nemat and Lyons [2] performed the experiment to study the effects of burnishing speed, feed, ball diameter, burnishing force, and the number of passes on the quality of the work surface produced and its wearing characteristics. The wearing characteristic of the surface was measured using a specially designed experimental rig. The burnishing force and the number of passes are two of the most important parameters that govern the functional properties of final surface.

Khabeery and Axir [3] conducted experimental work on vertical machining center to establish the effects of various burnishing parameters on the surface finish of 6061-T6 Aluminum alloys, including burnishing speed, ball material, lubricant, burnishing forces (depth of penetration), and feed. It was found that the burnishing speed and feed affect the surface finish.

Experimental work was carried out by Loh et al. [4] on a vertical machining center to establish the effects of four ball burnishing parameters, depth of penetration, feed, ball

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material, and lubricant on the surface hardness of the AISI 1045 specimens. A 68% increase in hardness was found.

Experimental work was carried out by Bonzid et al. [5] to establish the effects of four ball burnishing parameters: depth of penetration, feed, ball material, and lubricant on the surface roughness of AISI 1042 steel specimens. It has been noted that burnishing on AISI 1042 steel offers the best surface quality when using a small feed value. An analytical model has been defined to determine the relation between surface roughness and feed.

Luo et al. [6] studied the effects of burnishing parameters on the surface roughness of aluminum alloy burnished with a cylindrical surfaced polycrystalline diamond tool.

Shion and Chien [7] studied the effect of ball burnishing parameters on surface finish of a free form surface plastic injection mold on a machining center. Four burnishing parameters, namely, the ball material, burnishing speed, feed, and force, were selected as the experimental factors of Taguchi's design of experiments to determine the optimal burnishing parameters, which have a dominant influence on surface roughness.

Khabeery and Axir [8] studied the influence of orthogonal parameters on surface characteristics for various materials and found that increase in speed leads to considerable reduction in microhardness index. It was found that input parameters, namely, burnishing speed and depth of penetration have control effect on surface hardness.

Luo and Liu [9] presented a three-dimensional burnishing force model, which was studied, based on elastic–plastic contact mechanics and elastic–plastic impact mechanics. From this burnishing force model, a more ideal burnished surface can be obtained by deliberately controlling certain parameters.

Liu and Wang [10] designed and fabricated cylindrical polycrystalline diamond tools. Three components of burnishing force were established. The results show that the distribution of force is different between burnishing and turning. The effect of burnishing parameters on burnishing force and surface microhardness of the work piece were examined with theoretical analysis. It was concluded that the burnishing feed and depth are the most significant factors affecting burnishing force and surface hardness.

Adal and Ayman [11] studied the effect of initial burnishing parameters on nonferrous components. The results show that most of the parameters like ball diameter, intial surface hardness, roughness, and the use of different lubricants have significant effect on the burnishing process. Axir and Ibrahim [12] designed three ball burnishing tools and mounted on moving rest of a lathe by replacing three original adjustable jaws. Experimental work was carried out to study the effect of new burnishing tool and parameters such as burnishing speed, feed, and force on surface characteristics. The results showed that the above parameters play an important role in controlling the surface characteristics.

The intense interest centered on the development of ferrite-martensite dual-phase steels has led to numerous investigations. The content of such reports can be broadly classified into 2 groups:

(i) Physical metallurgy aspects of dual-phase steels; which incorporate information and understanding related to the evolution of dual-phase microstructures, the effects of various alloying elements on microstructure development, and the studies related to the kinetics of formation and nature of individual phases involved during phase transformation; and
(ii) Structure property relations in dual-phase steels; which include the attempts to search for correlations between the nature, volume fraction, size, and distribution of ferrite, martensite, and retained austenite, on one hand, and the strength, ductility, work hardening rate, fatigue life, corrosion resistance, toughness properties, on the other hand.

2. Objectives

In this article, a systematic study of effect of ball burnishing parameters on the surface hardness and wear resistance of high strength low alloy steel (HSLA) dual-phase steel specimens is presented.

The objective of this investigation can be categorized into five modules.

- To start with the optimization of the feed rate of the tool for a better surface hardness.
- To optimize the speed of the tool at an optimized feed rate to achieve a better surface hardness.
- To optimize the burnishing force at optimized feed rate and speed for a good surface hardness.
- To find out the effective lubricant at optimized feed rate, speed, and burnishing force to enhance a very good surface integrity.
- To optimize the burnishing force at optimized feed rate, speed lubricant, and diameter for good wear resistance.

3. Experimental work

The experimental work was conducted on a Kirloskar Turnmaster lathe. The use of the lathe for pre-machining and burnishing operations enabled a wide range of parameter settings to be easily obtained and adjusted. A specifically designed burnishing tool shown in Fig. 1 is the main element in the burnishing process. It accommodates a bearing steel ball of various diameters.

The ball is located in position by means of rod and screw. The tool was held stationary and rigidly on the

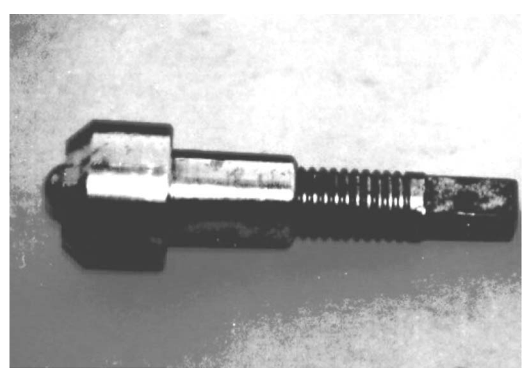

Figure 1.—Ball burnishing tool.

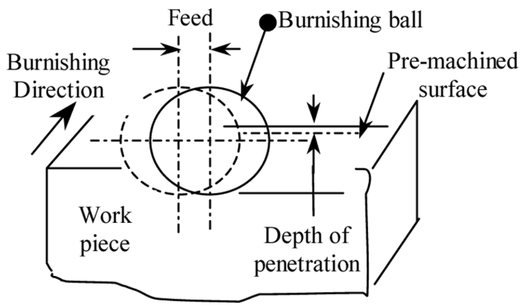

FIGURE 2.—Schematic illustration of terminologies.

tool post of the lathe machine. The depth of penetration and feed terminologies are shown in Fig. 2. The depth of penetration is the distance of the ball tip below the pre-machined surface and the feed is the horizontal distance between two successive ball centers.

Cylindrical dual-phase steel specimens were pre-machined to 18 mm diameter using a High-Speed Steel (HSS) tool. These specimens were cut to appropriate length of 200 mm and each was divided into 8 segments. Each segment was taken a length of 25 mm by making grooves in between each segment with the intent of exposing to different set of conditions during the experiment. The pre-machined surface hardness was measured. Without removing the specimens, the surfaces were burnished by varying the parameters.

Surface hardness of the pre-machined and burnished specimens was measured using Vickers hardness equipment. A pyramid diamond indenter with 136° apex angle was used and indentation load of 200 gf for 10 seconds was applied. A lathe tool dynamometer was used to measure cutting force and thrust force. The thrust force was taken as burnishing force.

The effect of ball burnishing on wear resistance of dual-phase steels was studied using turned ring shaped specimens. These specimens are held in mandrel and the mandrel is fixed in a lathe chuck. Burnishing tool is held in lathe tool dynamometer to facilitate the force measurement.

Dual phase steel specimens were burnished with different burnishing forces keeping optimum values of speed, feed, ball diameter, and lubricant constant. Initial weight of the test specimens was measured by using an analytical balance.

Wear experiments were conducted on these burnished specimens holding them in a lathe chuck through a mandrel and using a specially designed and fabricated fixture, which was fixed on the lathe bed. The experimental setup is shown in Fig. 3.

All the test pieces were subjected to similar wearing conditions. The speed of rotation of the test pieces during wearing is 500 rpm and a constant load of 5 kgf was applied. The specimens were in continuous contact with a tool steel under the load. After the test, the final weight of the test pieces was measured. The difference in weight is taken as the measure of wear resistance.

3.1. Material Composition

Commercial micro-alloyed steel supplied by Swedish Steel, (Oxelosund; Sweden) was selected as the starting material. The as-received steel was in the form of 20 mm thick hot-rolled plate in the tempered condition. The chemical composition of steel was ascertained with the help of a Baird optical emission spectrometer. The analyzed composition of steel is shown in Table 1.

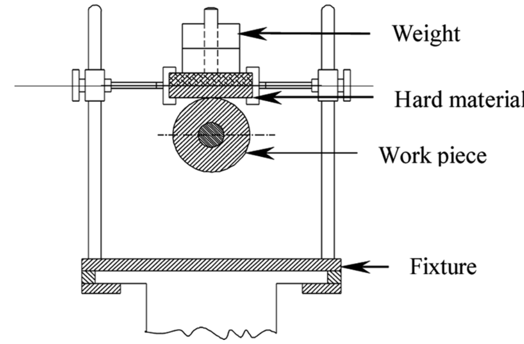

FIGURE 3.—Experimental setup to wear the dual-phase specimens.

TABLE 1.—Chemical composition (wt%) of HSLA steel.

C	Si	Mn	S	P	Cr	Mo	B	Nb
0.15	0.27	1.24	0.004	0.009	0.05	0.03	0.0012	0.022

3.2. Heat Treatment

The dual-phase microstructures were prepared by intermediate quenching (IQ). The IQ treatment consisted of a double quench operation. The specimens were first soaked at 920 ± 2°C for 30 min and were quenched in 9% iced-brine solution (−7°C). These were then held at inter critical temperatures (ICT) of 730° to 780°C for 60 min and were finally quenched in oil (25 ± 2°C). The heat treatment process is shown in Fig. 4.

3.3. Microstructural Characterization

Several stereological measurements were carried out to estimate the volume fraction of ferrite and martensite in the developed microstructures, shown in Figs. 5(a)–(f) using manual point counting technique and automatic areal

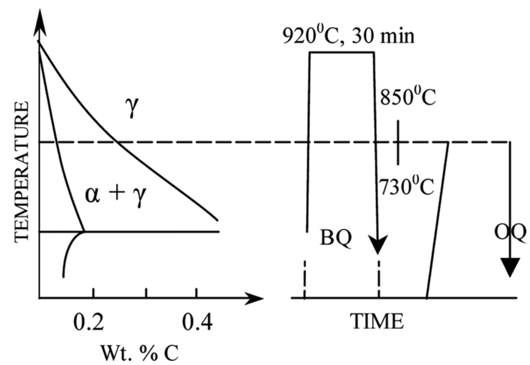

FIGURE 4.—Intermediate quench.

TABLE 2.—Results of volume fractions of ferrite and martensite.

Specimen (°C)	Volume % ferrite	Volume % martensite
730	66.90	33.10
740	62.45	37.55
750	59.82	40.18
760	54.95	45.05
770	51.54	48.46
780	48.10	51.90

analysis using a LECO image analyzer. Result of volume fraction of ferrite and martensite is shown in Table 2.

4. RESULTS AND DISCUSSION

The experiments are conducted covering all possible combinations of burnishing parameters and the results are shown in Tables 3–10.

TABLE 3.—Experimental values of surface hardness of dual-phase steels after burnishing at various feed rates.

Feed mm/rev	730°C	740°C	750°C	760°C	770°C	780°C
0.024	364	372	377	390	398	418
0.034	368	378	383	399	408	425
0.043	374	384	389	407	415	432
0.054	379	389	396	413	423	441
0.065	388	394	405	418	430	450
0.074	397	406	414	427	438	459
0.085	408	412	419	433	445	466
0.095	400	402	412	426	436	458
0.098	392	396	408	417	427	441

TABLE 4.—Experimental values of surface hardness after burnishing dual-phase steels at various speed rates (optimum feed = 0.085 mm/rev).

Speed m/min	730°C	740°C	750°C	760°C	770°C	780°C
5.65	376	380	385	394	406	422
11.3	387	389	396	404	415	438
17	398	404	409	419	426	446
22.62	409	416	424	432	444	460
28.27	392	409	416	426	437	451
34	384	400	407	418	423	442

TABLE 5.—Experimental values of surface hardness after burnishing dual-phase steels at various ball diameters (optimum feed = 0.085 mm/rev, optimum speed = 22.62 m/min).

Ball diameter mm	730°C	740°C	750°C	760°C	770°C	780°C
8	375	379	385	391	401	409
10	382	386	390	398	408	417
12.5	390	393	398	405	419	428
13.5	397	399	404	414	428	435
14.5	404	407	411	426	435	447
16.5	410	415	423	430	443	458
18.4	406	409	415	426	438	452
20.2	398	400	410	419	430	447

TABLE 6.—Experimental values of the surface hardness of dual-phase steel specimens burnished at various forces using Kerosene as lubricant (feed = 0.085 mm/rev, speed = 22.62 m/min, and ball diameter = 16.5 mm).

Burnishing force in kgf	730°C	740°C	750°C	760°C	770°C	780°C
5	323	331	340	347	356	361
10	327	338	346	355	362	369
15	334	345	351	360	369	375
20	339	351	358	366	374	381
25	345	357	364	371	379	386
30	340	350	359	367	372	380
35	336	343	351	362	365	374
40	332	339	342	357	360	369

TABLE 7.—Experimental values of the surface hardness of dual-phase steel specimens burnished at various forces using mixed oil as lubricant (feed = 0.085 mm/rev, speed = 22.62 m/min, and ball diameter = 16.5 mm).

Burnishing force in kgf	730°C	740°C	750°C	760°C	770°C	780°C
5	335	342	348	354	360	368
10	339	348	353	359	365	375
15	344	355	360	365	372	380
20	348	361	365	370	378	384
25	356	368	371	376	384	389
30	349	360	366	369	379	382
35	340	352	360	362	371	376
40	334	346	353	357	364	370

TABLE 8.—Experimental values of the surface hardness of dual-phase steel specimens burnished at various forces using SAE 40 oil as lubricant (feed = 0.085 mm/rev, speed = 22.62 m/min, and ball diameter = 16.5 mm).

Burnishing force in kgf	730°C	740°C	750°C	760°C	770°C	780°C
5	340	346	353	361	369	375
10	343	350	360	365	376	383
15	347	357	366	372	382	389
20	352	364	373	379	389	395
25	358	370	379	384	394	399
30	351	366	371	380	388	390
35	344	359	362	375	380	382
40	333	352	357	369	372	373

TABLE 9.—Experimental values of the surface hardness of dual-phase steel specimens burnished at various forces using grease as lubricant (feed = 0.085 mm/rev, speed = 22.62 m/min, and ball diameter = 16.5 mm).

Burnishing force in kgf	730°C	740°C	750°C	760°C	770°C	780°C
5	359	365	374	383	394	411
10	368	378	386	397	409	429
15	382	390	402	409	421	441
20	395	401	415	424	437	454
25	410	418	426	438	449	470
30	389	408	417	422	434	459
35	376	394	408	416	421	442
40	364	381	395	404	415	438

TABLE 10.—Experimental values of percentage reduction in weight of dual-phase steel specimens after wear test.

Burnishing force in kgf	730°C	740°C	750°C	760°C	770°C	780°C
5	3.22	2.98	2.87	2.53	2.44	2.32
10	2.97	2.86	2.74	2.47	2.39	2.28
15	2.84	2.75	2.61	2.41	2.31	2.16
20	2.73	2.64	2.55	2.38	2.27	2.09
25	2.65	2.42	2.37	2.32	2.16	1.98
30	2.77	2.69	2.51	2.49	2.28	2.07
35	2.8	2.76	2.68	2.62	2.37	2.24
40	2.94	2.89	2.72	2.7	2.41	2.33

4.1. Effect of Feed

The effect of feed on surface hardness of HSLA dual-phase steels is significant. It was observed from the experimental results plotted in Fig. 6, that with an increase in feed from 0.024 mm/rev to 0.085 mm/rev, the surface hardness increases. The optimum feed found from the experimental results is 0.085 mm/rev. At lower feed the plastic deformation is more intensive causing a greater increase in surface hardness, since at lower feed the number of times a ball deforms over the same spot is greater than at higher feed. The work hardening effect on the burnished surface is greater at lower feed and decreases with increase in feed. The reverse phenomena could be explained by observing the relationship between the feed and the force. For the same burnishing conditions as the feed increases,

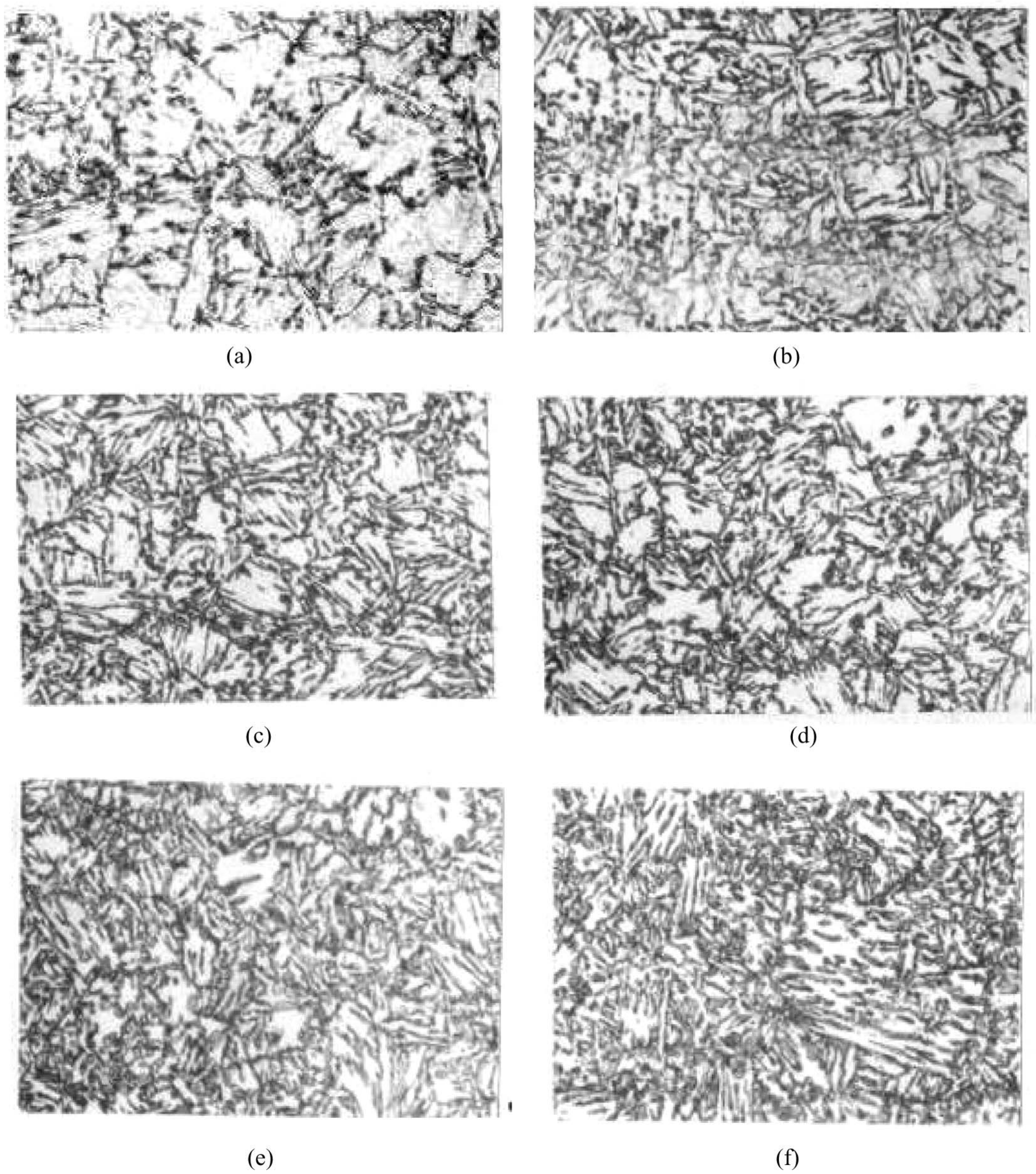

FIGURE 5.—Typical optical micrographs (750 X) of intermediate quench micro critical temperature at (a) 730°C, (b) 740°C, (c) 750°C, (d) 760°C, (e) 770°C and (f) 780°C

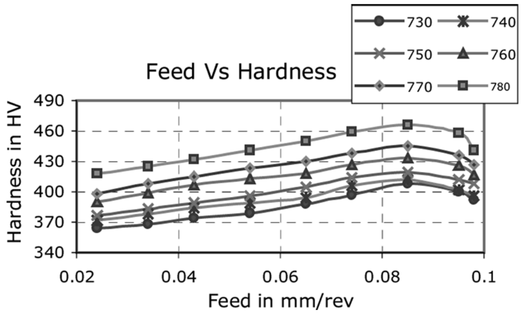

FIGURE 6.—Variation of surface hardness with burnishing feed.

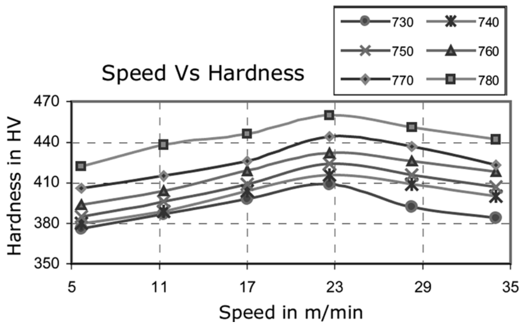

FIGURE 7.—Variation of surface hardness with burnishing speed.

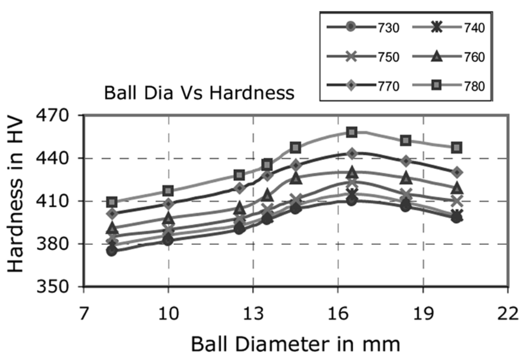

FIGURE 8.—Variation of surface hardness with burnishing ball diameter.

the normal and tangential force increases too, causing the surface hardness to increase. In this case, the increase in hardness due to the increase in force is greater than the reduction in hardness due to higher feed.

4.2. *Effect of Speed*

From the experimental values it was observed that the surface hardness increases with the increase in speed as shown in Fig. 7. At lower burnishing speeds, due to repeated burnishing causing flaking of surfaces, hardness is low. At higher speeds there is insufficient burnishing and surface hardness is low. Hence there is an optimum burnishing speed of 22.62 m/min, which gives the highest surface hardness.

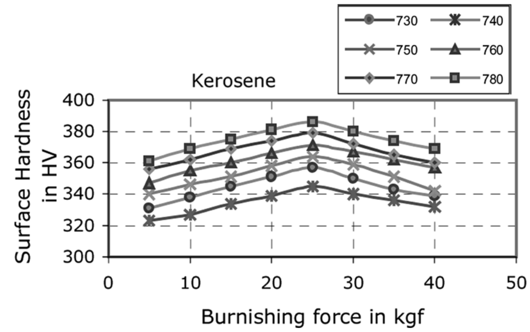

FIGURE 9.—Variation of surface hardness with burnishing force with kerosene as lubricant.

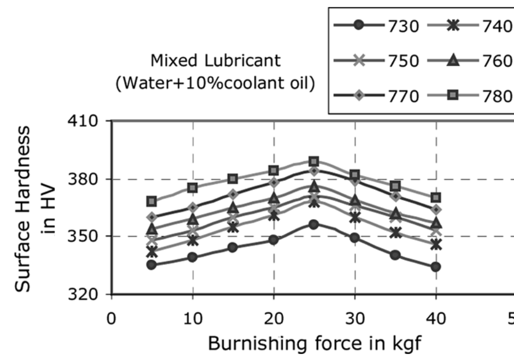

FIGURE 10.—Variation of surface hardness with burnishing force with mixed lubricant.

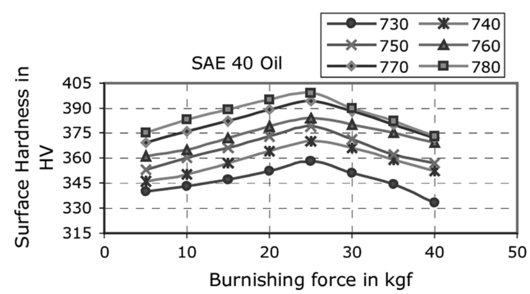

FIGURE 11.—Variation of surface hardness with burnishing force with SAE 40 oil as lubricant.

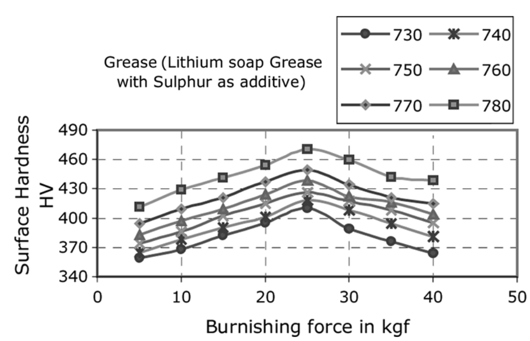

FIGURE 12.—Variation of surface hardness with burnishing force with grease as lubricant.

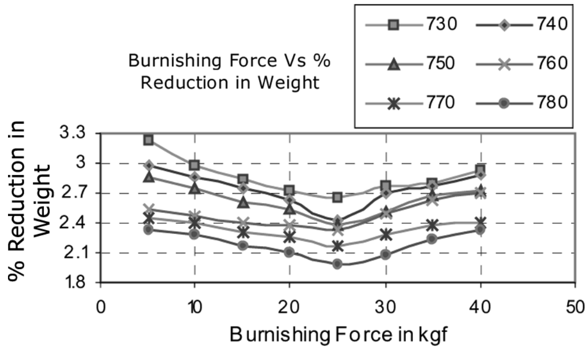

FIGURE 13.—Burnishing force vs. % reduction in weight.

4.3. *Effect of Ball Diameter*

From the experimental results it was observed that the surface hardness increases with the increase in ball diameter. The optimum size of ball observed was 16.5 mm, which is shown in Fig. 8. The increase in surface hardness with increase in ball size may be due to effective burnishing as curvature of ball increases. Once the ball size exceeds the optimum value, surface hardness deteriorates due to severe burnishing with higher curvature of the ball that leads to flaking effect on surfaces.

4.4. *Effect of Lubricant*

The effect of lubricant on surface hardness is found to be highly significant. It is observed from Figs. 9–12 that for the same burnishing conditions, burnishing with grease gives higher hardness values than kerosene, mixed lubricant, and SAE 40 oil. The application of lubricant has significant effect on any metal-cutting and forming processes. It will reduce the force of cutting and forming by reducing the friction conditions in those processes. In burnishing also,

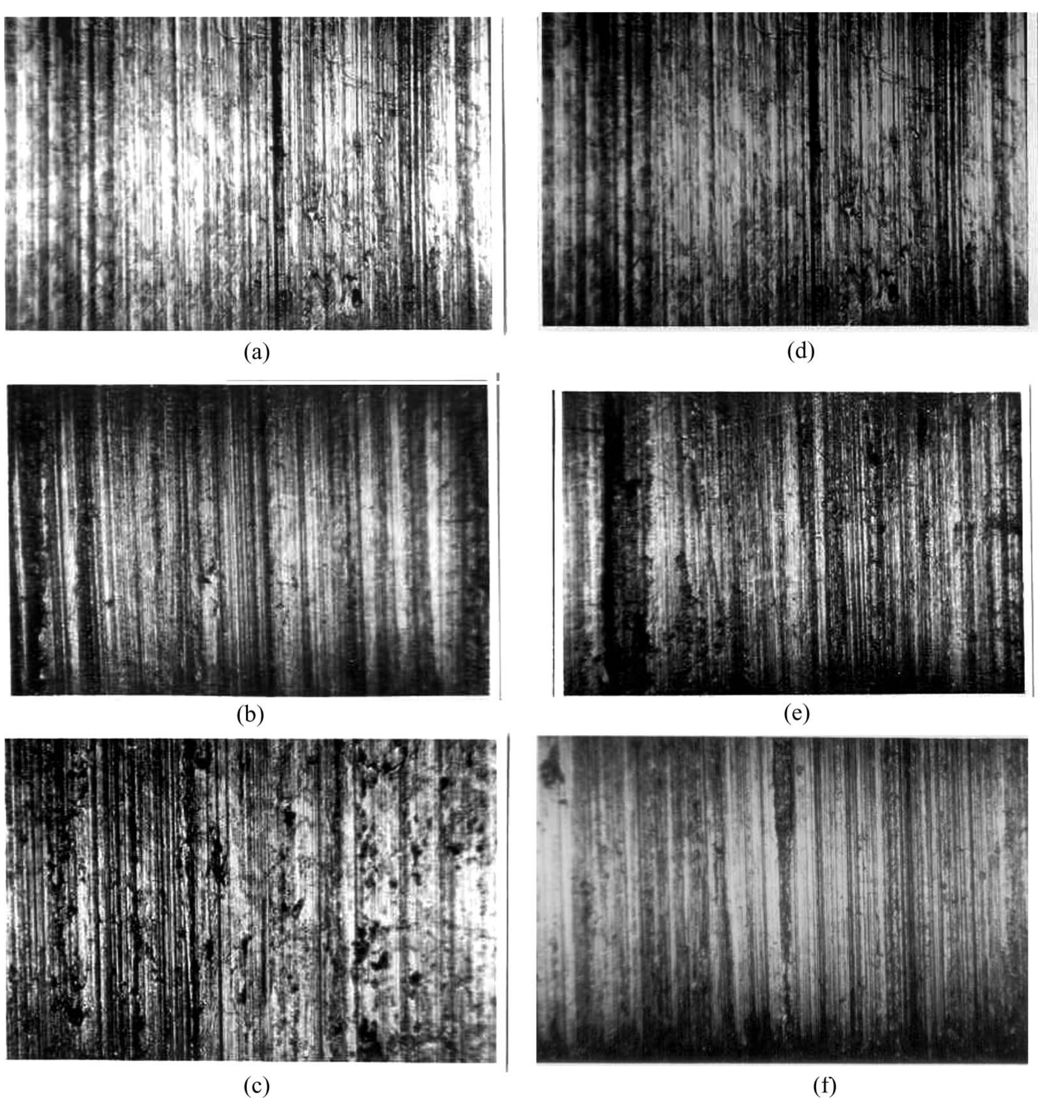

FIGURE 14.—Photographs of surface microstructure of HSLA dual-phase steels burnished at feed = 0.085 mm/rev., speed = 22.62 m/min, force = 25 kgf, ball diameter = 16.5 mm.

TABLE 11.—Experimental values of surface hardness of dual-phase steels before burnishing.

Specimen	Hardness values (HV)
730°C	282
740°C	291
750°C	300
760°C	314
770°C	326
780°C	348

lubricants will assist in easy deforming of surface layer with an applied burnishing force by providing favorable friction conditions between tool and work material.

4.5. Effect of Burnishing Force

From the experimental results it was observed that surface hardness increases with increase in burnishing force. After a certain burnishing force (optimum value) the surface hardness decreases. In this case, the optimum burnishing force found was 25 kgf. The increase in surface hardness is due to the plastic deformation of surfaces. But beyond the optimum value due to severe work hardening, flaking of surface layers will occur and hence hardness decreases.

For a particular burnishing condition, increase in burnishing force causes increase in work hardening and this can also increase the surface hardness.

4.6. Effect of Burnishing Force on Wear Resistance

From the experimental results it was observed that the percentage reduction in weight of the components decreases with increase in burnishing force. Beyond the optimum value of burnishing force (25 kgf) the percentage reduction in weight increases with increase in burnishing force. The reason for decrease in percentage reduction in weight with increase in burnishing force may be due to the plastic deformation of surface of the components by obtaining highest hardness. The increase in percentage of reduction in weight may be due to the distortion of the micro profile, excessive work hardening, flaking of surface layers, and reduction in hardness due to excess burnishing force.

5. Conclusions

The effect of ball diameter, speed, feed, and lubricant on surface hardness of HSLA dual-phase steels were studied. The main results obtained are as follows

- Optimum burnishing parameters on dual-phase steels were established and these can be used for maximum benefit of burnishing process.
- It can be concluded from the experimental results that the highest surface hardness and wear resistance can be achieved with 16.5 mm diameter ball, grease as lubricant, feed of 0.085 mm/rev, speed of 22.62 m/min, and burnishing force of 25 kgf.
- Experimental work shows that an improvement of about 30–45% in surface hardness of dual-phase steels (when compared to the initial hardness values as shown in Table 11) can be obtained by ball burnishing process.

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