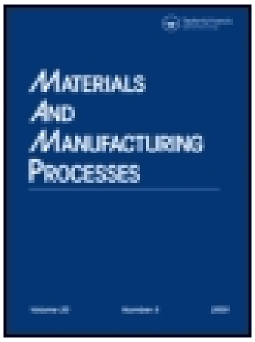

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Surface Hardening of High-Strength Low Alloy Steels (HSLA) Dual-Phase Steels by Ball Burnishing Using Factorial Design

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Burnishing is used increasingly as a finishing operation which gives additional advantages such as increased hardness, fatigue strength, and wear resistance. Experimental work based on 3^4 factorial design was carried out to establish the effects of ball burnishing parameters on the surface hardness of high-strength low alloy steels (HSLA) dual-phase (DP) steel specimens. Statistical analysis of the results shows that the speed, feed, lubricant and ball diameter have significant effect on surface hardness.

Keywords Burnishing; Composite microstructures; Compressive residual stress; Double quenching; Dual-phase (DP); Factorial design; Fatigue resistance; Hardness; High-strength low alloy; Inter-critical temperature; Kinetics of formation; Optomechanical; Tribology; Volume fraction; Work hardening.

1. Introduction

The finishing of metals with a hardened surface layer has attracted the interest of researchers, e.g., those in the optomechanical industry. The functional performance of a component, such as fatigue life, load-bearing capacity, and wear, depends on its surface characteristics such as hardness, induced residual stresses, and topography. Czichos and Habig [1] studied the tribological behavior of medium carbon steel. They found that different wear values, wear patterns, and wear mechanisms result depending on various factors, material parameters (e.g., hardness), operating variables (e.g., kinematics), geometry of the tribological system, and interfacial conditions. Studies by Kudryavtsev [2] have established the beneficial effects of residual compressive stresses and work hardening in improving the fatigue strength of various materials. Burnishing, a plastic deformation process, is commonly used to achieve good surface finish [3, 4]. Unlike machining processes, burnishing was also found to give several additional desirable surface characteristics [5, 6], i.e., higher fatigue strength, increased surface hardness due to work hardening, and higher wear resistance. In order to utilize the increased hardness effectively of the burnishing process, the parameters affecting surface hardness have to be established. In this article, a systematic study of the effects of ball burnishing parameters on the surface hardness of high-strength low alloy steels (HSLA) dual-phase (DP) steel specimens is reported. For the experiments to be performed efficiently, statistical techniques such as 3^4 factorial designs were used.

The global energy crisis has thrown open perpetual challenges to the materials technologists to evaluate newer materials with improved combinations of high strength, ductility, and toughness. This led to the emergence of a series of composite microstructures, in which DP steels represent a distinguished class. The specific potentials of DP steels that have been technologically exploited are their superior ductility and formability characteristics compared to HSLA or conventional plain carbon steels of similar strength level. The path of evolution of DP steels has been reported by numerous investigators directed towards understanding the role of a large number of microstructural variables, which influence their mechanical properties.

Commonly, low carbon steels exhibiting ferrite ($\sim$80%)–martensite ($\sim$20%) microstructures are referred to as DP steels; however, these may contain small amounts of retained austenite and/or bainite depending on alloy content and processing parameters. The initial reports on DP steels can be traced back to early 1980s [7, 8]. These steels become of technological interest because of their attractive combinations of superior strength and formability properties over the conventional HSLA steels, particularly for applications in weight saving engineering components.

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

(i) Physical metallurgy aspects of DP steels; which incorporate information and understanding related to the evolution of DP microstructures, the effects of various alloying elements on microstructure developments, and the studies related to the kinetics of formation and nature of individual phases involved during phase transformation; and
(ii) Structure property relations in DP 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,

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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

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

Specimen	Volume % ferrite	Volume % martensite
740°C	62.45	37.55

corrosion resistance, toughness properties, on the other hand.

2. Objectives

The objective of this investigation can be categorized into two modules:

- To study the characteristics of developed DP microstructures containing volume fractions of martensite and ferrite;
- To determine the optimum burnishing parameters for highest hardness on DP specimens;
- The hardness of the DP steel is optimized by interpretation of tool feed, peed, and lubricant, referred in Figs. 4–6.

3. Experimental work

3.1. Material

Commercial micro-alloyed steel supplied by M/s 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 *Baird optical emission spectrometer*. The analyzed composition of steel was found to be in agreement with the suppliers' certification as shown in Table 1.

3.2. Heat Treatment

The DP 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 an inter critical temperature (ICT) of 740°C for 60 min and were finally quenched in oil (25 ± 2°C). The heat treatment process is shown in Fig. 1.

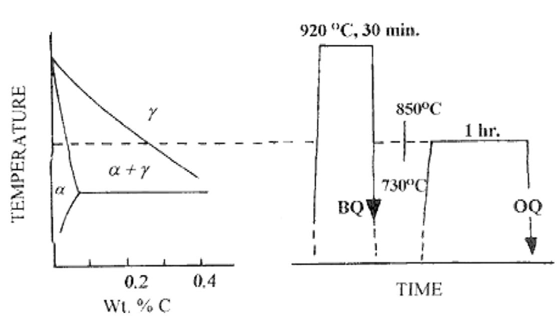

FIGURE 1.—Intermediate quench.

3.3. Microstructural Characterization

Several stereological measurements were carried out to estimate the volume fraction of ferrite and martensite in the developed microstructures using manual point counting technique and automatic areal analysis using a LECO image analyzer (Table 2).

3.4. Factorial Design

There are numerous advantages associated with the use of factorial design in the conducting of experiments: It is more efficient than the conventional one-factor-at-a-time experiments commonly employed by researchers, and also enables the study of both the main and interaction effects between factors. Further, should a parameter (e.g., surface hardness) needs to be minimized (or maximized) with respect to a combination of factors, factorial design will give a combination near to the minimum (or maximum), whereas the one-factor-at-a-time procedure will not.

In the 3^4 factorial design used, four factors (burnishing parameters) were studied. The four factors selected were: ball diameter, lubricant, feed, and speed. Each quantitative and qualitative factor has three numerical values and three types of material, respectively, commonly known as three "levels". The four factors and their respective levels are shown in Table 3.

The experimental work was conducted on Kirloskar Turn Master lathe machine. The ball-burnishing tool shown in Fig. 2 is the main element in the burnishing process. It accommodates carbon chromium Steel ball of various diameters. The burnishing tool was held stationary and rigidly on the tool post of the lathe machine. The feed terminology is shown in Fig. 3, which is the horizontal distance between two successive ball centers.

The work pieces were selected as cylindrical bars of 18 mm diameter. The bars were cut to appropriate length 250 mm and each was divided into 8–10 segments. Each segment was grooved to a length of 20 mm with the intend

TABLE 3.—Experimental burnishing factors and levels.

Factor	Level
Ball diameter	12.5 mm
	13.5 mm
	16.5 mm
Lubricant	Grease (Servo make)
	Kerosene
	Mixed lubricant (Water + Coolant Oil)
Feed	0.07 mm/rev
	0.08 mm/rev
	0.09 mm/rev
Speed	2.262 m/min
	3.393 m/min
	5.656 m/min

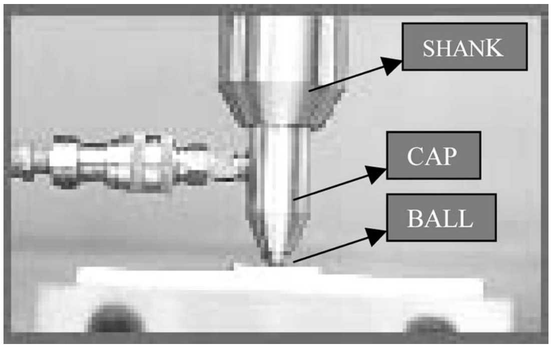

FIGURE 2.—Ball burnishing tool assembly.

of exposing the surface of the groove to a different set of conditions during the experiment. The hardness of the pre-machined and burnished surfaces was measured using Vickers hardness equipment. A pyramid diamond indentor with 136° apex angle was used and an indentation load of 200 gf for 10 sec was applied. Experimental results for hardness values comprising all possible burnishing conditions are shown in Table 4 for different volume percentages of ferrite and martensite.

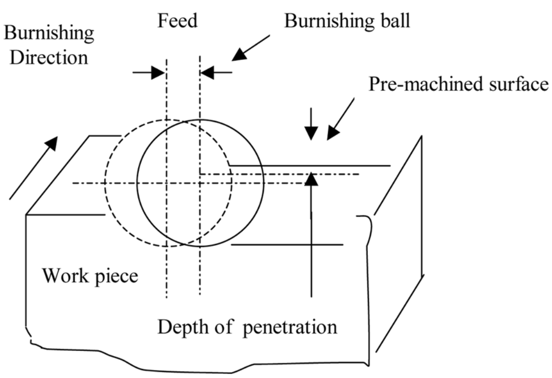

FIGURE 3.—Schematic illustration of terminologies.

4. Results and discussion

4.1. Effect of Ball Diameter

The surface hardness of burnished specimen is dependent on the ball diameter. It is evident from the experimental results shown in Figs. 4(a)–(c) with the values registered in Table 4. The ball diameter of 16.5 mm diameter gives the highest hardness value, which is about 60% higher than the pre-machined surface hardness. Under the same burnishing conditions, the balls with different diameters give different surface hardness values (see Figs. 4–6). The higher contact surface in between the ball and the specimen makes the specimen surface harder than the other two balls of smaller diameter [see Figs. 4(a)–(c)]. The compressive residual stresses induced by the ball with higher diameter during operation enhances a better surface hardness, found to be a distinction of the product.

4.2. Effect of Lubricant

The application of lubricant has significant effect on any metal-cutting and metal-forming process. It will reduce the force of cutting and forming by reducing the friction in those processes. In burnishing also, lubricants will assist in easy deforming of surface layer with applied feed and speed. From the experimental results it is found that the effect of lubricant on surface hardness is significant. Under the burnishing conditions, burnishing with grease gives higher hardness than kerosene and mixed lubricant. This is achieved by the eminent properties of the grease like viscosity, adherence, and better specific heat capacity. This is represented in Figs. 5(a)–(c).

4.3. Effect of Speed and Feed

The effect of speed of the specimen on surface hardness is significant. The optimum speed is found from Table 4 is 22.62 m/min. The work hardening effect on the burnished surface is greater at lower feed and decreases with increase in feed. This is because at lower feed the number of times a ball deforms over the same spot is greater than at higher feed. Thus at lower feed the plastic deformation is more intensive, causing a greater increase in surface hardness. It is evident from the experimental results that the surface hardness increases with an increase in feed.

TABLE 4.— Volume % of ferrite = 62.45, volume % of martensite = 37.55, and inter critical temperature = 740°C, Pre-machined surface hardness = 261 HV.

		Ball dia = 12.5 mm			Ball dia = 13.5 mm			Ball dia = 16.5 mm		
Speed m/min	Feed mm/rev	Kerosene	Grease	Mixed lubricant	Kerosene	Grease	Mixed lubricant	Kerosene	Grease	Mixed lubricant
22.62	0.07	268	314	277	272	342	281	288	392	285
	0.08	271	326	281	277	355	286	294	418	289
	0.09	273	334	283	281	363	290	299	406	292
33.93	0.07	274	316	288	278	353	292	293	367	294
	0.08	279	328	291	283	368	295	297	372	296
	0.09	282	335	297	288	371	299	303	381	300
56.56	0.07	281	321	290	284	367	297	300	379	298
	0.08	285	331	294	288	378	305	308	385	307
	0.09	288	338	299	291	383	308	316	393	318

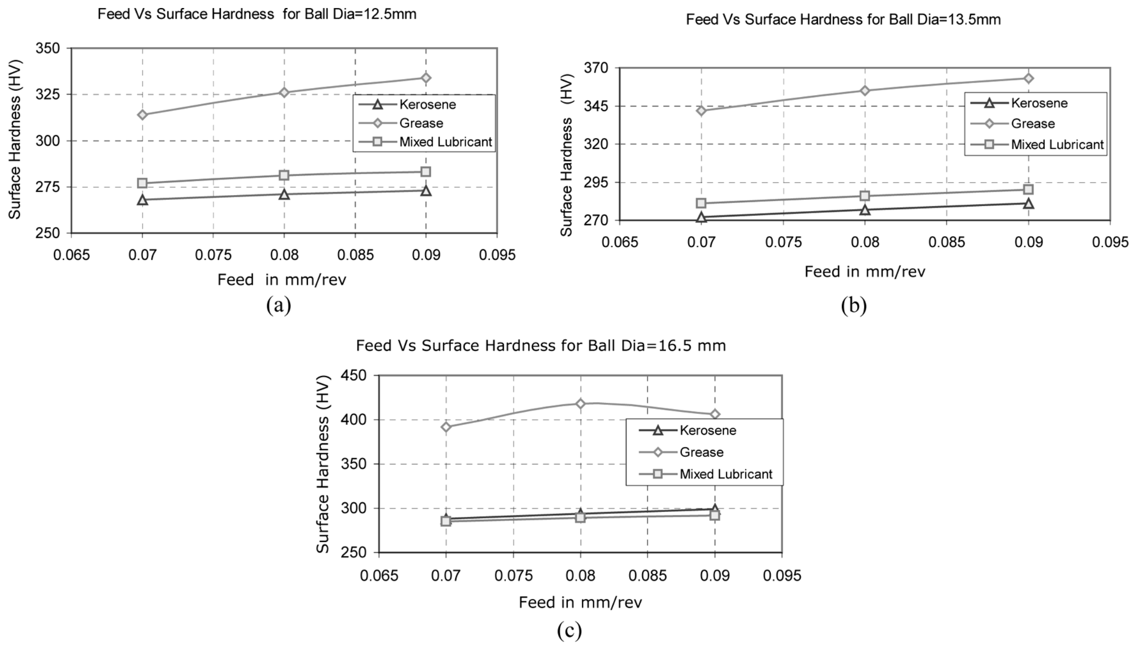

FIGURE 4.—Relationship between feed and surface hardness for 22.62 m/min speed.

5. CONCLUSION

The effect of ball diameter, speed, feed, and lubricant on surface hardness of HSLA DP Steels were studied. The main results obtained are as follows

- Optimum burnishing parameters on DP steels were established and these can be used for maximum benefit of burnishing process.
- It can be concluded from the experimental results that highest surface hardness can be achieved by 16.5 mm diameter ball, grease as lubricant, feed of 0.08 mm/rev, and speed of 22.62 m/min.
- Experimental work shows that an improvement of about 55%–60% in surface hardness of DP Steels can be obtained by ball burnishing process.

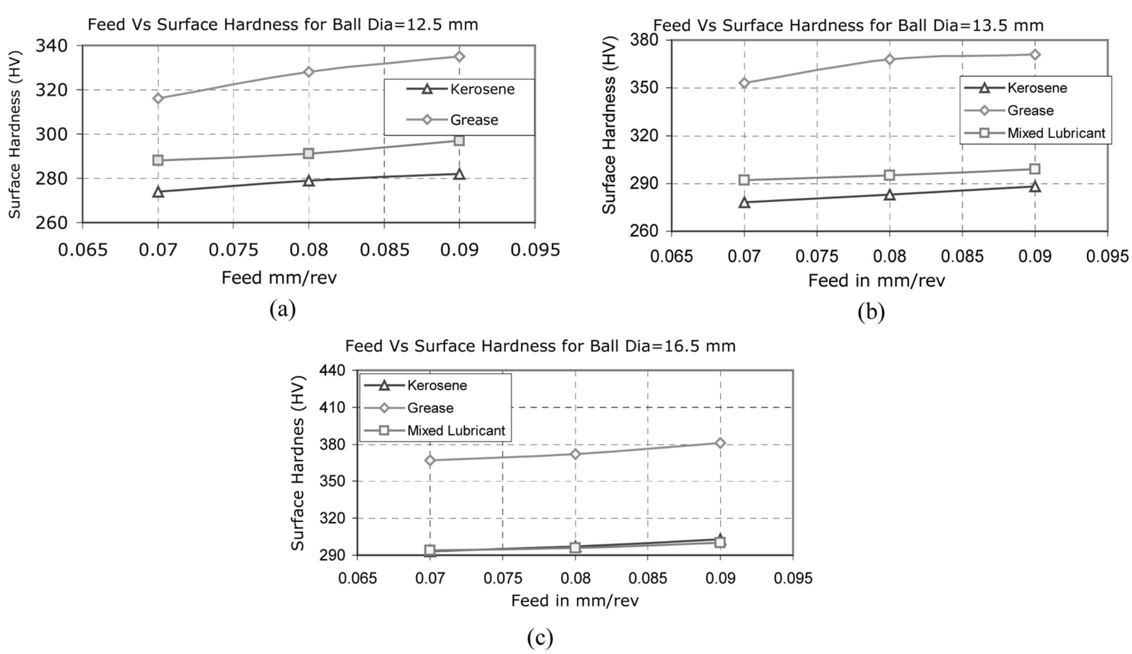

FIGURE 5.—Relationship between feed and surface hardness for 33.93 m/min speed.

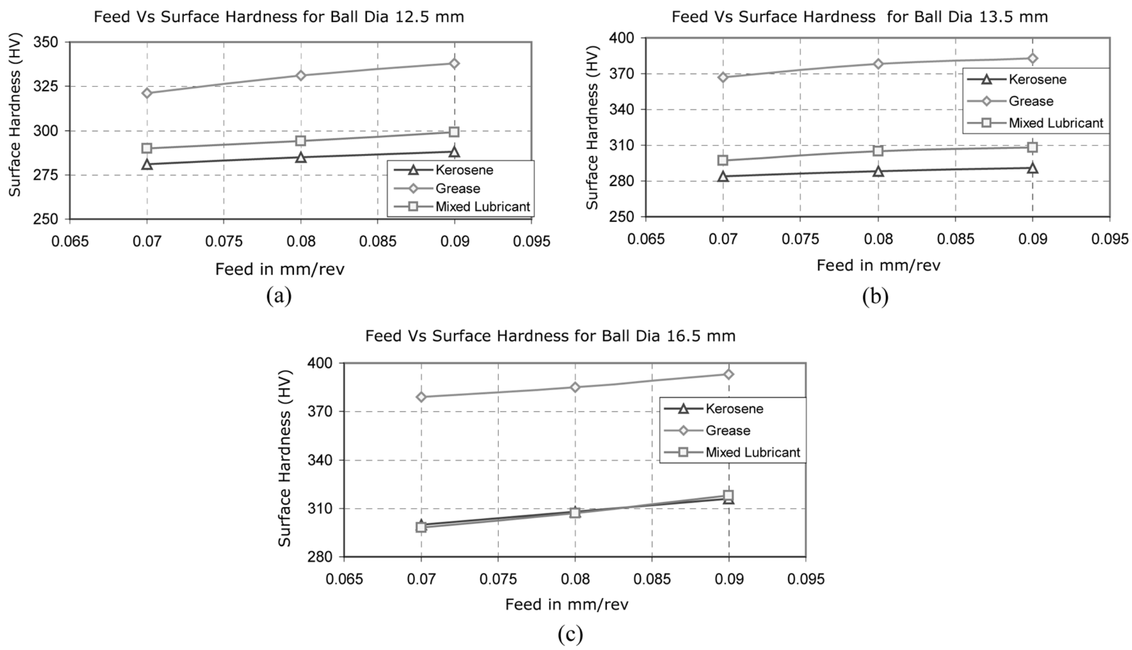

FIGURE 6.—Relationship between feed and surface hardness for 56.56 m/min speed.

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