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An investigation into roller burnishing

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Abstract

Burnishing, a plastic deformation process, is becoming more popular as a finishing process: thus, how to select the burnishing parameters to reduce the surface roughness and to increase the surface microhardness is especially crucial. This paper reports the results of an experimental program to study the influence of different burnishing conditions on both surface microhardness and roughness: namely, burnishing speed, force, feed, and number of passes. Also, it reports the relationship between residual stress and both burnishing speed and force. The residual stress distribution in the surface region that is orthogonally burnished is determined using a deflection etching technique. Mathematical models are presented for predicting the surface microhardness and roughness of St-37 caused by roller burnishing under lubricated conditions. Variance analysis is conducted to determine the prominent parameters and the adequacy of the models. From an initial roughness of about R_a 4.5 μm, the specimen could be finished to a roughness of 0.5 μm. It is shown that the spindle speed, burnishing force, burnishing feed and number of passes have the most significant effect on both surface microhardness and surface roughness and there are many interactions between these parameters. The maximum residual stress changes from tensile to compressive with an increase in burnishing force from 5 to 25 kgf. With a further increase in burnishing force from 25 to 45 kgf, the maximum residual stress increases in compression.

1. Introduction

The function performance of a machined component such as fatigue strength, load bearing capacity, friction, etc. depends to a large extent on the surface as topography, hardness, nature of stress and strain induced on the surface region. Nowadays, about 50% of the energy supplied is lost in the friction of elements in relative motion [1]. Roughness values less than 0.1 μm are required for good aesthetic appearance, easy mould release, good corrosion resistance, and high fatigue strength.

During recent years, however, considerable attention has been paid to the post-machining metal finishing operations such as burnishing which improves the surface characteristics by plastic deformation of the surface layers [2]. Burnishing is essential in a cold-forming process, in which the

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metal near a machined surface is displaced from protrusions to fill the depressions. Beside producing a good surface finish, the burnishing process has additional advantages over other machining processes, such as securing increased hardness, corrosion resistance and fatigue life as a result of producing compressive residual stress. Residual stresses are probably the most important aspect in assessing integrity because of their direct influence on performance in service. Thus, control of the burnishing process (burnishing conditions) in such a way as to produce compressive residual stresses in the surface region could lead to considerable improvement in component life.

A comprehensive classification of burnishing tools and their application has been given by Shneider [3]. A literature survey shows that work on the burnishing process has been conducted by many researchers and the process also improves the properties of the parts, e.g. higher wear resistance [4,5] increased hardness [6–8], surface quality [2,9,10] and increased maximum residual stress in compression [11]. The parameters affecting the surface finish are: burnishing force, feed rate, ball material, number of passes, workpiece material, and lubrication [2].

This paper examines the use of the roller burnishing process to give a good surface integrity for steel-37. To explore the optimum combination of burnishing parameters in an efficient and quantitative manner, the experiments were designed based on the response surface methodology (RSM) with central composite rotatable design. The effect of four burnishing parameters on the surface finish and surface microhardness were investigated, namely: burnishing speed, force, feed rate, and number of passes. The relationship between the most important burnishing parameters (speed and force) and residual stress were studied.

2. Experimental work

Specimens were turned and burnished on a center lathe model DIZ 450×1600 (WMW, Germany). The workpiece material was Steel-37 (0.20% C; 0.30% Si; 0.80% Mg; 0.05% P; 0.05% S) of hardness 220 H_v. It was selected because of its importance in industry and its susceptibility to degradation when burnished, through surface and subsurface damage. The work material was received in the form of tube and then machined into two different groups. In the first group, the form of the workpieces were short tubes (Fig. 1(a)) and they were used for surface roughness and microhardness tests. In the second group, the shape of the workpieces were rings (Fig. 1(b)) and were used for residual stress tests. Fig. 1 shows the dimensions of workpieces of each group. The workpieces of the first group were prepared with two recesses such that each specimen could be used in two different conditions. Portion C in Fig. 1(a) was left without burnishing for comparison purposes with portions A and B which were burnished in burnishing tests. A feed rate of 0.1 mm/rev, depth of cut of 0.25 mm, and spindle speed of 600 rpm were used as the turning conditions. The surface finish of the pre-machined and burnished specimens were measured using a surftest-402 system. The pre-machined surface roughness obtained was in the range from 5.5 to 6.5 μm (R_a). Lubricant was then applied to the pre-machined surface. Without removing the specimen the surface was burnished.

The specially designed burnishing tool is shown in Fig. 2. A roller bearing having an outside diameter of 22 mm and a width of 6 mm was fitted to the tool, the factors under investigation in the experiments were: burnishing speed, burnishing force, feed rate, and number of passes.

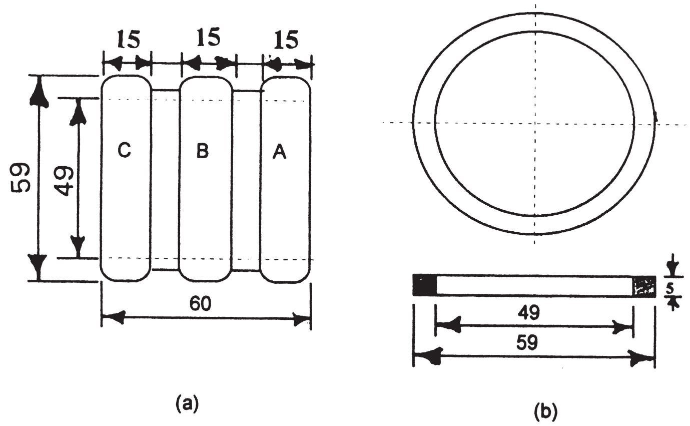

Fig. 1. Workpiece geometry.

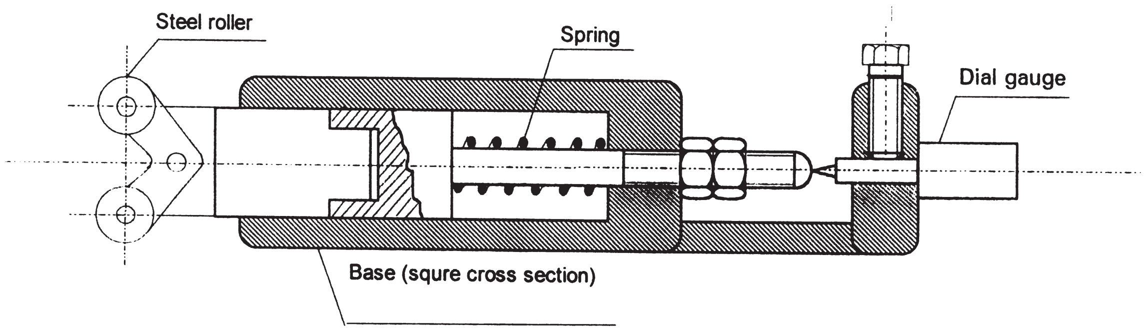

Fig. 2. Roller burnishing tool.

3. Experimental design

In this investigation, experiments were designed on the basis of the experiments design technique that has been proposed by Box and Hunter [12]. A detailed description of this method is presented elsewhere [13]. According to a central composed-second-order rotatable design with four independent variables, the total number, N, of experiments is determined to be 31. The cutting conditions and their coded levels are summarized in Table 1. The experimental design was not used during the study of the effect of both burnishing speed and force on the residual stress.

4. Results and discussion

4.1. Presentation of results

Table 2 shows the results of the first group of the thirty-one experiments carried out in this research. Using the results presented in Table 2 the response surface for the surface roughness

Table 1
Summary of burnishing conditions

Parameters	Symbol	Levels in code form −2	−1	0	1	2
Burnishing speed, rpm	X_1	50	150	250	350	450
Burnishing force, kgf	X_2	5	15	25	35	45
Burnishing feed rate, mm/rev	X_3	0.06	0.13	0.20	0.27	0.34
Number of passes	X_4	1	2	3	4	5
Roller diameter		22 mm				

R_a, and the surface microhardness H_v, as functions of the fourth parameters used in this work are deduced as the following final equations:

$$H_v = 329.3 + 6.3X_1 + 18.8X_2 - 6.6X_3 + 20.2X_4 - 8.0X_{11}^2 - 6.3X_{22}^2 \quad (1)$$
$$\ldots + 7.6X_{44}^2 - 10.8X_1X_3 + 11.6X_1X_4 - 8.8X_2X_4$$

$$R_a = 1.34 + 0.22X_1 + 0.43X_2 + 0.524X_3 + 0.186X_4 + 0.194X_{11}^2 + 0.418X_{22}^2 \quad (2)$$
$$\ldots + 0.23X_{44}^2 + 0.294X_1X_2 + 0.394X_1X_4 + 0.223X_2X_3 + 0.318X_2X_4$$

It should be noted from the final equation that there are some coefficients omitted. These coefficients are non-significant according to Student's *t*-test that determined the significant and non-significant parameters. Also, the final models tested by variance analysis (*F*-test) indicated that the adequacy of the models was established.

In these models that were obtained by the RSM method, the relationship between the burnishing responses (microhardness and surface roughness) and the significant variations are shown in Figs. 3–14.

Fig. 3, Fig. 4 and Fig. 5 present the effect of the burnishing speed on the burnished surface microhardness at various force, feed and number of passes, respectively. From these figures, it can be seen that an increase in the spindle speed to more than 230 rpm leads to a decrease in the surface hardness.

Fig. 3, Fig. 6 and Fig. 7 show the effects of the burnishing force on the hardness of the surface burnished at different spindle speed, feed, and number of passes. The hardness of the surface considerably increases with increasing burnishing force within the range used in this work.

The influence of the feed rate on the surface microhardness is shown in Fig. 4, Fig. 6 and Fig. 8. The microhardness of burnished surface increases as the feed rate is reduced. Fig. 4 shows an interaction between feed rate and spindle speed. An increase in feed rate at low spindle speed increases the surface microhardness whereas an increase in feed rate at high spindle speed decreases the surface microhardness.

The influence of the number of burnishing passes across the surface on the surface (tool pass) is shown in Fig. 6, Fig. 7 and Fig. 8. In general, the microhardness of the burnished surface increases as the number of passes is increased. There is an interaction between the number of passes and spindle speed. At high spindle speed, the increase in the hardness with an increase in

Table 2
Experimental conditions and results

No.	Burnishing speed		Burnishing force		Burnishing feed		Number of passes		Surface roughness	Surface hardness
	code X_1	actual v	code X_2	actual F	code X_3	actual f	code X_4	actual n	R_a (μm)	H_v
1	−1	(150)	−1	(15)	−1	(0.14)	−1	(2)	1.20	253
2	1	(370)	−1	(15)	−1	(0.14)	−1	(2)	0.60	257
3	−1	(150)	1	(35)	−1	(0.14)	−1	(2)	0.97	312
4	1	(370)	1	(35)	−1	(0.14)	−1	(2)	1.07	343
5	−1	(150)	−1	(15)	1	(0.28)	−1	(2)	3.00	301
6	1	(370)	−1	(15)	1	(0.28)	−1	(2)	2.10	241
7	−1	(150)	1	(35)	1	(0.28)	−1	(2)	2.60	356
8	1	(370)	1	(35)	1	(0.28)	−1	(2)	2.90	302
9	−1	(150)	−1	(15)	−1	(0.14)	1	(4)	0.50	306
10	1	(370)	−1	(15)	−1	(0.14)	1	(4)	1.60	336
11	−1	(150)	1	(35)	−1	(0.14)	1	(4)	1.10	349
12	1	(370)	1	(35)	−1	(0.14)	1	(4)	1.20	383
13	−1	(150)	−1	(15)	1	(0.28)	1	(4)	2.00	330
14	1	(370)	−1	(15)	1	(0.28)	1	(4)	2.10	318
15	−1	(150)	1	(35)	1	(0.28)	1	(4)	2.80	312
16	1	(370)	1	(35)	1	(0.28)	1	(4)	5.80	366
17	−2	(46)	0	(25)	0	(0.20)	0	(3)	1.40	280
18	2	(480)	0	(25)	0	(0.20)	0	(3)	2.90	343
19	0	(230)	−2	(5)	0	(0.20)	0	(3)	1.60	301
20	0	(230)	2	(45)	0	(0.20)	0	(3)	4.50	336
21	0	(230)	0	(25)	−2	(0.06)	0	(3)	0.50	362
22	0	(230)	0	(25)	2	(0.34)	0	(3)	1.50	290
23	0	(230)	0	(25)	0	(0.20)	−2	(1)	1.62	337
24	0	(230)	0	(25)	0	(0.20)	2	(5)	2.97	411
25	0	(230)	0	(25)	0	(0.20)	0	(3)	0.80	330
26	0	(230)	0	(25)	0	(0.20)	0	(3)	1.50	318
27	0	(230)	0	(25)	0	(0.20)	0	(3)	1.80	306
28	0	(230)	0	(25)	0	(0.20)	0	(3)	1.60	324
29	0	(230)	0	(25)	0	(0.20)	0	(3)	1.00	336
30	0	(230)	0	(25)	0	(0.20)	0	(3)	1.60	333
31	0	(230)	0	(25)	0	(0.20)	0	(3)	0.90	339

the number of passes is much more than that at low spindle speed. Fig. 7 shows another interaction between the number of passes and burnishing force. The increase of the surface microhardness as a result of increasing the number of passes at low forces is much more than that at high forces.

Fig. 9, Fig. 10 and Fig. 11 present the effect of the spindle speed on the burnished surface roughness at various forces, feed and number of passes, respectively. It can generally be seen that at low burnishing force and/or low number of passes and at any value of feed, the surface roughness decreases with an increase in spindle speed. The best results were obtained at spindle speeds in the range from 230 to 370 rpm. However, an increase in spindle speed at high burnishing force and/or high number of passes deteriorates the surface roughness. This means that there is

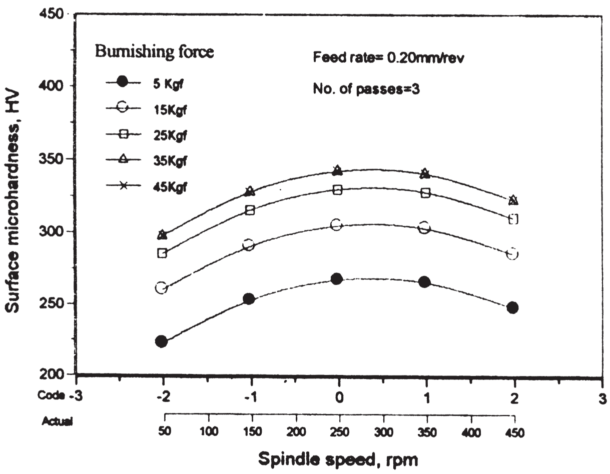

Fig. 3. Effect of spindle speed on the microhardness at different forces (kgf).

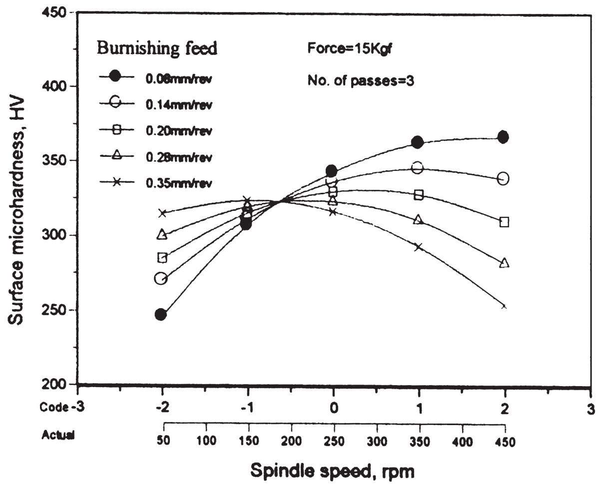

Fig. 4. Effect of spindle speed on the microhardness at different feeds (mm/rev).

an interaction between spindle speed and both burnishing force Fig. 9 and number of passes Fig. 11.

Fig. 9, Fig. 12 and Fig. 13 show the effect of burnishing force on the surface roughness for different speeds, feed, and number of passes, respectively. The best results were obtained at burnishing force in the range from 25 to 35 kgf. Also from these figures, it can be seen that the burnishing force interacts with each one of the other parameters. At very high spindle speed, feed rate and number of passes, an increase in the burnishing force results in an increase in surface roughness.

Fig. 10, Fig. 12 and Fig. 14 show the effect of burnishing feed rate on the surface roughness

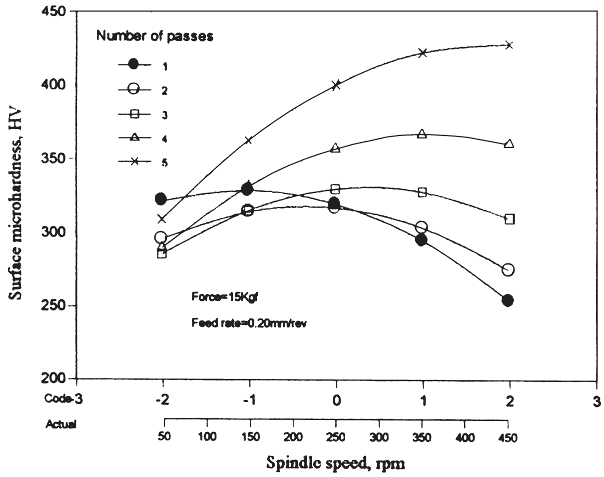

Fig. 5. Effect of spindle speed on the microhardness at different passes.

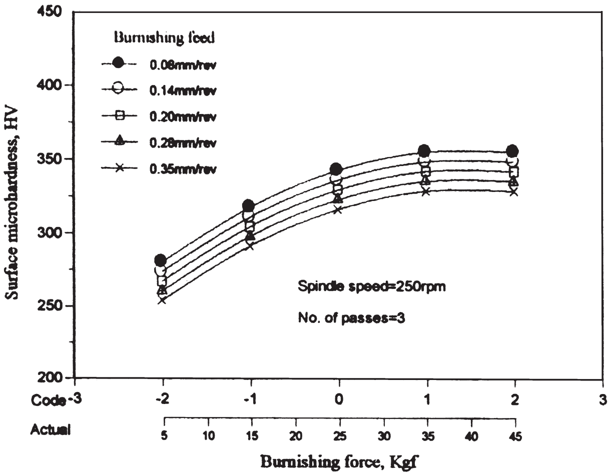

Fig. 6. Effect of burnishing force on the microhardness at different feeds (mm/rev).

for different speeds, force, and number of passes, respectively, in three dimensions and contour. It can be seen that an increase in feed rate is not beneficial in the roller burnishing process.

The influence of the number of burnishing passes across the surface on the surface roughness is shown in Fig. 11, Fig. 13 and Fig. 14. The best results were obtained at the number of burnishing passes in the range from 2 to 4. It should be noted that at high spindle speed and/or burnishing force an increase in the number of passes deteriorates the surface roughness as shown in Fig. 11 and Fig. 13.

The results of the second group tests are shown in Fig. 15 and Fig. 16. Fig. 15 shows typical residual stress profiles in the surface region of workpieces burnished at a burnishing force of 25 kgf and a burnishing time of 10 s for several speeds. It can be seen that the residual stress at the burnished surface is low compressive and increases to a maximum value at depths in the range

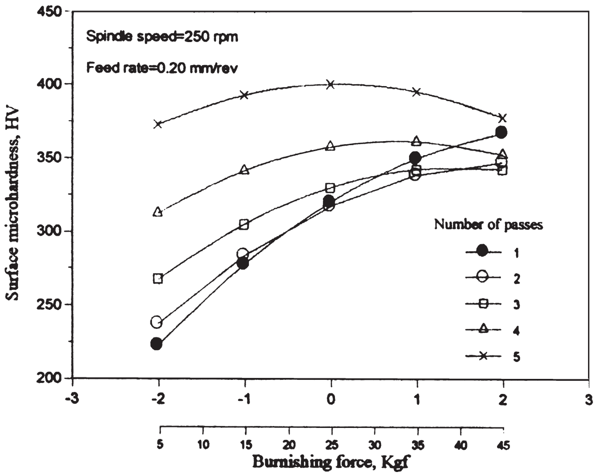

Fig. 7. Effect of burnishing force on the microhardness at different passes.

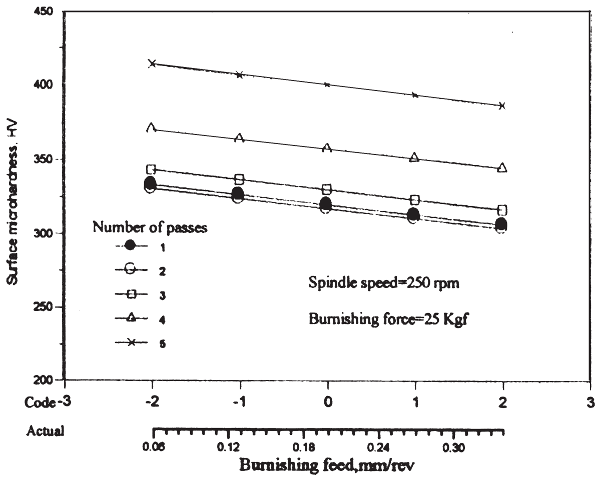

Fig. 8. Effect of burnishing feed on the microhardness at different passes.

from 100 to 150 μm beneath the burnished surface. The stress then decreases gradually with a further increase in depth beneath the burnished surface becoming negligible at large depths.

Fig. 16 shows the residual stress distribution in the surface region at a burnished speed of 230 rpm for 10 s, at different burnishing forces. It can be seen that the residual stress at the burnished surface is low and increasing very rapidly with an increase in the depth beneath burnished surface to a maximum tensile residual stress (at low forces) and/or to a maximum compressive residual stress (at high forces), then it decreases gradually with a further increase in depth becoming vanishingly small.

The variation of maximum residual stress at different burnishing speeds is shown in Fig. 17. It can be seen that an increase in burnishing speed to 350 rpm produces a significant increase in the

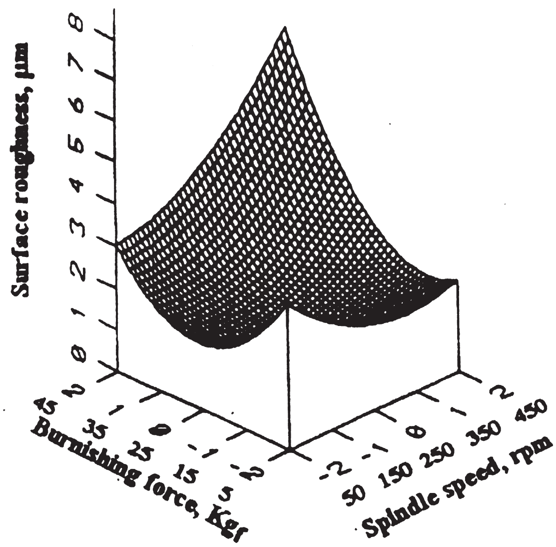

Fig. 9. 3D curve of interaction of spindle speed, force and surface roughness.

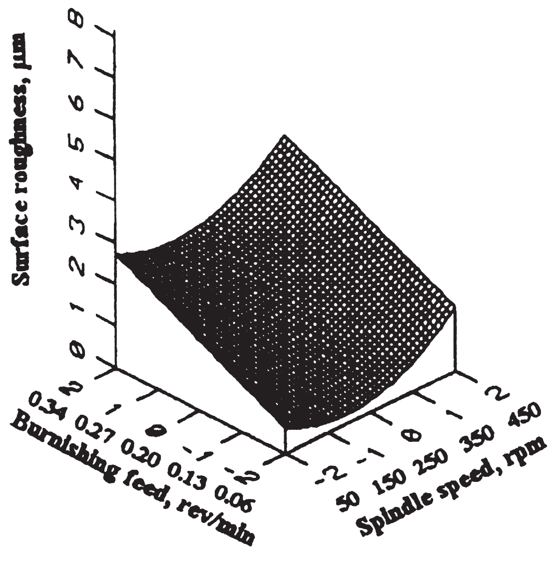

Fig. 10. 3D curve of interaction of spindle speed, feed and surface roughness.

maximum compressive residual stress. With a further increase in burnishing speed the maximum compressive residual stress decreases and may change to tensile residual stress.

Fig. 18 shows the variation of the maximum residual stress with burnishing force. It can be seen that the maximum tensile residual stress first decreases in tension and changes gradually to compressive residual stress with an increase in burnishing force.

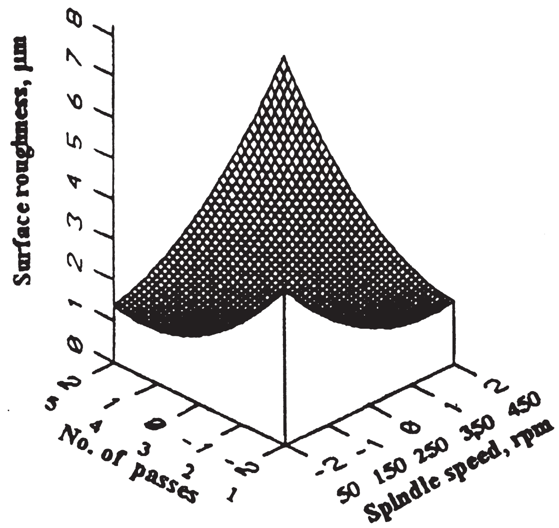

Fig. 11. 3D curve of interaction of spindle speed, number of passes and surface roughness.

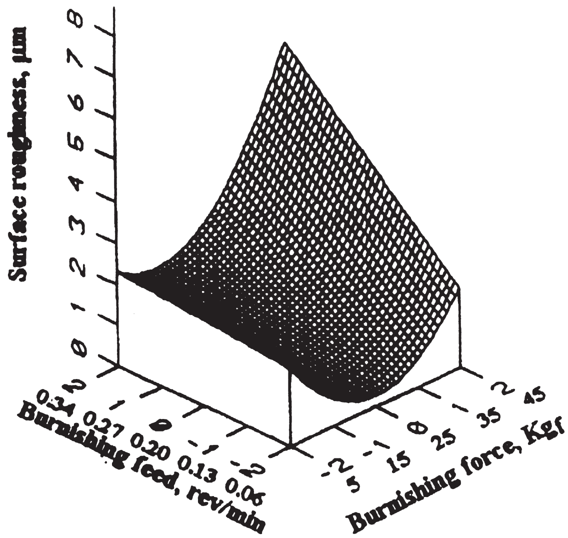

Fig. 12. 3D curve of interaction of force, feed and surface roughness.

4.2. General discussion

In this section, the main reasons for the results presented in the previous section will be presented and discussed. The deterioration of the surface microhardness and/or surface roughness in the burnishing process at high burnishing speeds as shown in Fig. 3 and Fig. 4 for hardness and Fig. 9, Fig. 10 and Fig. 11 for surface roughness is believed to be caused by the chatter that

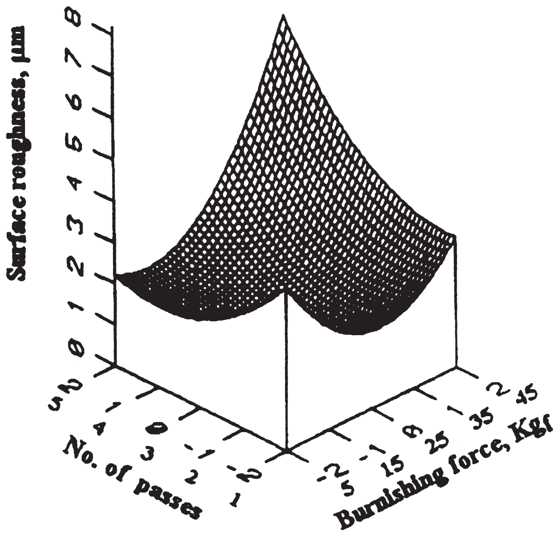

Fig. 13. 3D curve of interaction of force, number of passes and surface roughness.

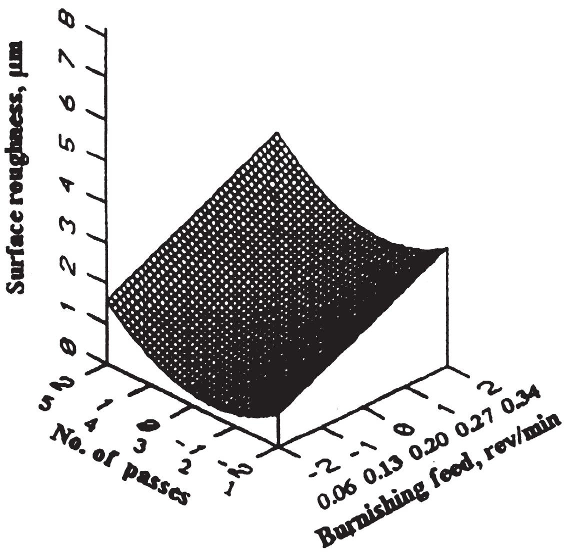

Fig. 14. 3D curve of interaction of feed, number of passes and surface roughness.

results from the unsuitability of the burnishing tool crossing the workpiece surface. However, as shown in Fig. 5, at high burnishing speeds the microhardness of the burnished surface increases with an increase in the number of passes. It is believed that the increase in the number of passes increases the surface hardness as a result of the increasing impact between the burnishing tool and the workpiece surface.

Burnishing force is one of the very important burnishing parameters that affects the results of

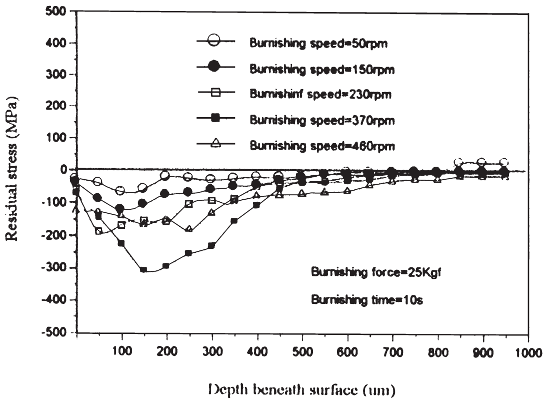

Fig. 15. Residual stress distribution in the surface region for different speeds.

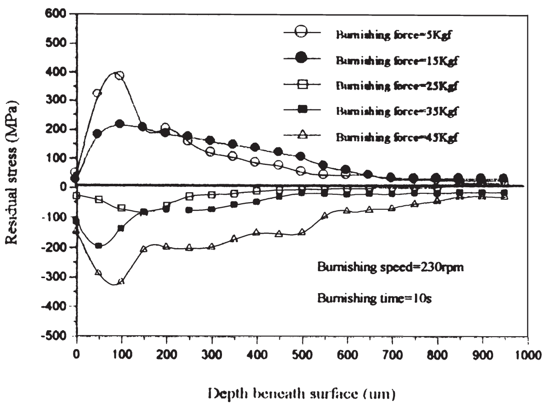

Fig. 16. Residual stress distribution in the surface region for different forces.

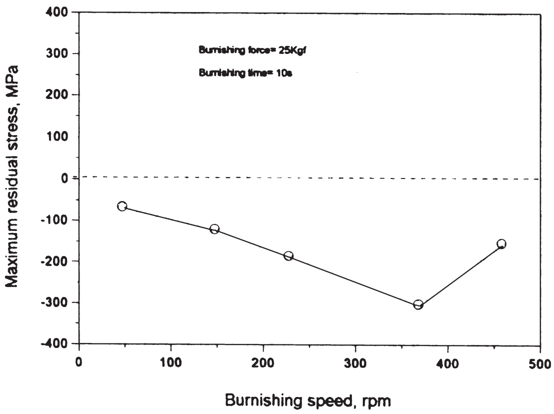

Fig. 17. Effect of burnishing speed on the maximum residual stress.

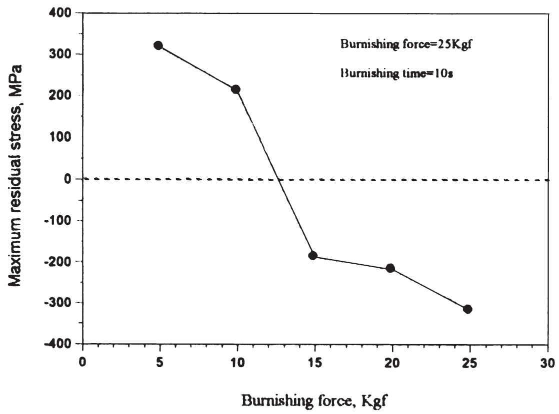

Fig. 18. Effect of burnishing force on the maximum residual stress.

this process. The increase in burnishing force causes an increase in the amount of surface deformation as the tool passes along the surface of the workpiece. This will lead to an increase in the work hardening of the surface layers, which have been affected by plastic deformation, so that surface hardness will increase via the increase in burnishing force, as shown in Fig. 6. However, the results of the burnished surface roughness show that when burnishing steel-37 with forces of more than 25 kgf, the surface finish is deteriorated, as can be seen in Fig. 9, Fig. 12 and Fig. 13. This may be because high forces causes shear failure in the subsurface layers which, in turn, results in the flaking.

The effect of burnishing feed on both surface microhardness and surface roughness is generally similar. The effect of feed is very clear on the high feed rate, the high surface roughness and/or low surface microhardness. It is better, then, to select low feeds because the deforming action of the burnishing tool is greater and metal flow is regular at low feed. However, as shown in Fig. 4, the effect of feed on the surface microhardness depends upon the spindle speed. When carrying out the burnishing process at very low spindle speed, an increase in feed leads to an increase in surface microhardness. The deforming action of the roller burnishing tool is too high so that the flaking occurs at a combination of very low spindle speed with very low feed.

The results show that the number of passes is one of the most significant factors affecting the surface hardness and surface roughness. This is obvious because the repeating of the burnishing process on the same workpiece leads to an increase in the structural homogeneity which results in an increase in the surface responses. However, in some cases, increasing the number of passes more than a certain number deteriorates the results because of the overhardening and consequent flaking of the surface layers.

It is believed that the complex distribution of the residual stress in the surface region of the burnished workpiece is produced by mechanical, thermal and metallurgical effects that occur simultaneously. The residual stress can be tensile or compressive depending on the volume changes. The problem is further complicated because these factors often act synergistically.

The maximum compressive residual stress increases with an increase in burnishing speed up to about 380 rpm, as shown in Fig. 17. This is anticipated because the mechanical, thermal and metallurgical effects would be greater at high speeds. At low burnishing speeds, however, it was observed that the burnishing process was accompanied with pitting and flaking formation on the surface region, and temperatures in the surface region are insufficient to overcome work hardening produced by plastic deformation.

The increase in the burnishing force produces an increase in both the depth of plastic deformation in the surface region and the extent of surface work hardening. It is believed that the increase in surface region deformation brought about the maximum residual stress, as may be seen in Fig. 18.

5. Conclusion

The results of the burnishing process are quite complicated, and many factors affect its results. How to find the optimal burnishing conditions and how to control the results are very important for industry. According to this research, the following conclusions may be drawn:

1. A good correlation between the experimental and predicted results derived from the model was exhibited. Thus, using the proposed procedure, the optimum roller burnishing conditions should be obtained to control the surface responses of other materials.
2. It was shown that the spindle speed, burnishing force, burnishing feed and number of passes have the most significant effect on both surface microhardness and surface roughness, and there are many interactions between these parameters.
3. The principle factors which affect the results of both surface microhardness and roughness are the tool chatter that occurs when using a high spindle speed and then the impact between tool and workpiece surface. The workpiece overhardening and then flaking generally occurs when using a combination of high burnishing force with a high number of passes, and the great deforming action of the tool and the increase of structural homogeneity of the surface layers that occurs when using low burnishing feed.
4. The recommended spindle speeds that result in high surface microhardness and good surface finish are in the range from 150 to 230 rpm.
5. The recommended burnishing force for high surface microhardness is about 35 kgf, whereas for good surface finish (low surface roughness) it is about 25 kgf.
6. The best results for both responses were obtained at the lowest value of the burnishing feed used in this investigation.
7. The best results for surface microhardness were obtained at a high number of passes whereas for the surface finish they were obtained in the range from 3 to 4 passes.
8. Compressive residual stress is generated in the surface region of a ring-shaped workpiece of St-37 burnished using a force of more than 25 kgf and high speeds under lubricated orthogonal conditions.
9. The residual stress is at a maximum near the surface and decreases with an increase in the depth beneath the surface.

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