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ORIGINAL ARTICLE

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The relationship between surface roughness and burnishing factor in the burnishing process

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Abstract This investigation examines burnishing using a microscopic perspective and elucidates the mechanism of surface roughness improvement by asperity deformation. This study uses tribology theory to propose a burnishing factor L_b to explain why the same burnishing result can be obtained in different burnishing conditions. The burnishing factor was determined by appropriate experiments, and the results demonstrated that a quadric curve relationship exists between surface roughness and burnishing factor and is analogous to the Stribeck curve in lubrication regimes.

Keywords Burnishing · Boundary lubrication · Elastic tool holder

1 Introduction

Finishing is becoming increasingly important in the production of machine and instrument components, and increasing attention is being paid to surface finish quality. A good surface finish has a positive and lasting effect on the functioning of machine parts, affecting wear resistance, load-carrying capacity, tool life, and fatigue. Poor surface finish may increase wear, invalidate tolerances, and increase the power requirements of the mechanism.

Burnishing is one of the no-chip finishing processes for surface engineering. Conventional machining processes such as milling and turning inevitably produce irregular surfaces, and thus post-processing is required to reduce surface roughness, involving grinding, lapping, polishing, honing, and so on. Unlike these traditional methods, which are based on chip removal, burnishing, which utilises surface plastic deformation, easily produces a smooth surface, and can also increase the fatigue strength and wear resistance of a workpiece, owing to the residual compressive stress and the work hardening of the material on the surface [1].

Various researchers have investigated the burnishing process, and have studied the effects of workpiece materials, tool materials, tool shapes, contact types, and process parameters with different machine tools [2, 3,4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. This research has reached conclusions relating to the roughness model and plastic deformation theory applied to the burnished zone, and so on.

This work investigates the effect of the burnishing process parameters on burnished surface roughness. The burnishing process was carried out using an elastic tool holder, which could adjust the burnishing load. The burnished surface roughness was analysed from the perspective of tribological theory. This study proposes a useful parameter for assessing the optimum combination of burnishing parameters.

2 Relationship between surface roughness and burnishing factor (L_b)

In burnishing, the tool is applied to the surface of the workpiece with a constant load and speed. To prevent adhesive wear between the interfaces of the tool and workpiece, a lubricant is generally used in burnishing. The burnishing system thus comprises a tool, a workpiece and lubricant, and can be considered to be a tribosystem [14]. The lubrication model can consist of three main lubrication regimes:

1. Hydrodynamic lubrication (and Elastohydrodynamic, EHD, lubrication)
2. Partial EHD lubrication or mixed lubrication
3. Boundary lubrication [15]

According to the lubrication models, the tool and workpiece sliding behaviour during burnishing can be considered to be subject to boundary lubrication (and in

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some other conditions to mixed lubrication). Therefore, the loading acting on the workpiece surface during burnishing is supported mostly by the asperities that are in contact with the tool surface. Furthermore, the contact stresses cause elastic and plastic deformations of the asperities contacted to produce a finished surface after burnishing. During boundary lubrication, the plastic deformation behaviour of loaded asperities depends on the level of contact stress. If the contact stress exceeds some critical level, serious plastic deformation of contacting asperities occurs and the temperature of the contact point rises quickly. Furthermore, adhesive behaviour between the interfaces is sometimes induced causing roughness in the burnished surface. On the other hand, if the contact stress is below some critical value, the plastic deformation of the contacted asperities can be ignored, and the surface roughness of the burnished surface is not obviously improved. Consequently, an optimum combination of parameters exists in the burnishing process, which optimises the roughness of the burnished surface.

As noted previously, the parameters that influence the roughness of the burnished surface, can be summarised as follows:

1. Hardness and ductility of workpiece and tool
2. Lubricant viscosity and fluidity, as well as the properties of boundary films
3. Level of contact stress
4. Relative sliding speed of the burnishing surface to that of the tool
5. Tool feed

The above analysis indicates that the ratio of the lubricant film thickness and average asperity height determine the quality of the burnished surface. Hamrock and Dowson proposed a dimensionless minimum film thickness in the isothermal elastohydrodynamic lubrication condition, expressed as follows [16]

$$\widetilde{H}_{\min} = 3.63U^{0.68}\,G^{0.49}\,W^{-0.073}\left(1 - e^{-0.68k}\right)$$
$$k = 1.03\left(\frac{R_y}{R_x}\right)^{0.64} \tag{1}$$

where:

- U denotes dimensionless speed parameter.
- G represents dimensionless material parameter.
- W is a dimensionless load parameter.
- R_x and R_y denote effective radius in the x and y directions.
- k represents an ellipticity parameter, from 1 (circle contact) to 8 (approaching line contact).

Although boundary and elastohydrodynamic lubrication differ, following the elastohydrodynamic film the broken lubrication model becomes a boundary lubrication regime. Significantly, the minimum film thickness of the elastohydrodynamic lubrication indicates the direction to search for a suitable burnishing condition, despite the optimal burnishing process being located in the boundary lubrication regime. The elastohydrodynamic film fails in the boundary lubrication regime but offers the information necessary to determine the optimal burnishing parameters. According to the characteristics of burnishing, as analysed above, a burnishing factor L_b, which can be used to assess the roughness of the burnished surface which is proposed in this study, can be defined as follows:

$$L_b = C^{\alpha} V^m \eta^r \left(\frac{H}{P_{\max}}\right)^n \tag{2}$$

where:

- L_b denotes burnishing factor.
- H represents workpiece hardness (MPa).
- $P_{\max}$ is the maximum contact stress between tool and workpiece (MPa).
- V denotes relative sliding speed of burnishing surface and tool (m/s).
- C represents the correction factor of boundary film.
- η is the dynamic viscosity of lubricant (Pa·s).
- α denotes a constant dependent on the property of the lubricant additive, and $\alpha = 0$ if the lubricant is additive free.
- n, m, r are constants.

Therefore, the relationship between the roughness of the burnished surface and the burnishing factor L_b can be expressed as follows:

$$\text{Roughness} = A \bullet f(L_b) \tag{3}$$

where:

- A is a constant which depends on feed, initial surface roughness of the workpiece and the roughness of the tool surface.

3 Relationship between asperity deformation and burnishing factor L_b in burnishing process

During burnishing, the tool acting on the workpiece surface causes plastic deformation of the asperities. Theoretically, the lubricant film will support most burnishing loading when the lubricant film thickness exceeds the average height of the asperities. In this condition the burnishing factor is relatively large, causing little plastic deformation of the higher asperities contacted and having little effect on the surface quality. Surface asperities and the tool surface contact directly when the lubricant film is too thin, causing most of the burnishing load to be carried by the asperities contacted. This condition decreases the relative burnishing factor, causes serious wear behaviour, and increases the roughness of the burnished surface. Consequently, an

Table 1 The conditions of the burnishing process

Maximum contact pressure (GPa)	Speed (m/s)	Feed (mm/rev)	Lubricant	Contact angle
1.23/1.78/2.11/2.36	0.079/0.52/2.64	0.032/0.127/0.506	Water-miscible cutting fluids/ Heavy-duty motor oil (SAE 40)	135°

optimal burnishing condition exists, where the deformation of the contacted asperities is effectively induced without causing wear on the rubbing surface. This optimal burnishing condition can produce a high quality burnished surface. Approaching the optimal burnishing condition requires either adjusting burnishing loading or speed, or lubricant viscosity. Theoretically, the optimal burnishing parameter should be in the boundary lubrication regime and can be assessed by the burnishing factor L_b. To identify this concept, this investigation conducted a series of experiments burnishing on medium carbon steel.

4 Experiment

This study systematically searches for the optimal condition for burnishing using the burnishing factor L_b.

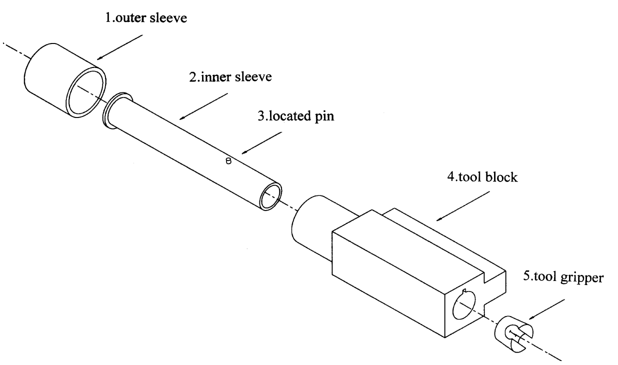

Fig. 1 Schematic diagram of flexible tool hold

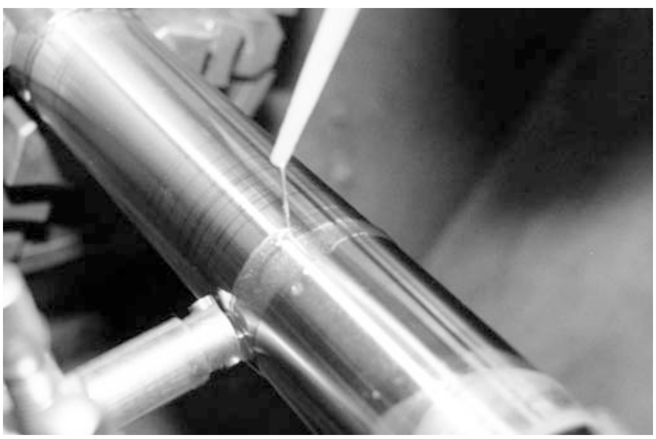

Fig. 2 Contact of tool and workpiece during burnishing

A lathe was employed for burnishing, and an AISI 1045 steel bar with a diameter of 60 mm was used as the work material, having a microstructure consisting of ferrite and pearlite. A surface polished WC bar of diameter 6 mm and length 15 mm was used as the burnishing tool. Before burnishing, the workpiece surface was machined to Rz–D = 3.96 μm, and during burnishing, water-miscible cutting fluids and heavy-duty motor oil (SAE 40) was employed as the lubricant, respectively. Table 1 shows the burnishing conditions. To adjust the burnishing loading, this study employed a flexible tool holder, shown in Fig. 1. Figure 2 shows the type of tool and workpiece used in the burnishing test. After burnishing the specimen surface

Table 2 Roughness of burnished surface under different conditions with heavy-duty motor oil (SAE 40)

Feed (mm/rev)	Burnishing sliding speed (m/s)	Maximum contact pressure (GPa)	Roughness (μm)
0.032	0.079	1.23	1.61
		1.78	0.81
		2.11	0.33
		2.36	0.38
	0.52	1.23	2.22
		1.78	1.19
		2.11	0.38
		2.36	0.27
	2.64	1.23	1.15
		1.78	0.61
		2.11	0.29
		2.36	0.16
0.127	0.079	1.23	1.63
		1.78	1.13
		2.11	0.65
		2.36	0.54
	0.52	1.23	2.23
		1.78	1.58
		2.11	0.69
		2.36	0.37
	2.64	1.23	1.6
		1.78	0.88
		2.11	0.38
		2.36	0.33
0.506	0.079	1.23	1.7
		1.78	1.46
		2.11	0.72
		2.36	0.67
	0.52	1.23	2.37
		1.78	1.89
		2.11	1.12
		2.36	0.57
	2.64	1.23	1.52
		1.78	1.1
		2.11	1.38
		2.36	0.68

Table 3 Roughness of burnished surface under different conditions with water-miscible cutting fluids

Feed (mm/rev)	Burnishing sliding speed (m/s)	Maximum contact pressure (GPa)	Roughness (μm)
0.032	0.079	1.23	1.09
		1.78	0.74
		2.11	0.41
		2.36	0.84
	0.52	1.23	1.29
		1.78	0.64
		2.11	0.56
		2.36	0.78
	2.64	1.23	1.59
		1.78	0.89
		2.11	1.27
		2.36	5.68
0.127	0.079	1.23	1.22
		1.78	0.92
		2.11	0.55
		2.36	0.71
	0.52	1.23	1.23
		1.78	0.76
		2.11	0.66
		2.36	0.63
	2.64	1.23	1.69
		1.78	1.85
		2.11	2.39
		2.36	5.5
0.506	0.079	1.23	1.48
		1.78	1.07
		2.11	0.68
		2.36	0.48
	0.52	1.23	1.56
		1.78	1.03
		2.11	0.65
		2.36	0.49
	2.64	1.23	1.85
		1.78	2.28
		2.11	3.1
		2.36	2.28

Fig. 3 Worn surface in burnishing

was inspected using a HOMMELWERKE surface tester.

4.1 Results and discussion

Tables 2 and 3 list the surface roughness of the burnished specimens in various conditions. Table 2 shows that with oil lubricant an optimally burnished surface was obtained close to the maximum (2.36 GPa) contact

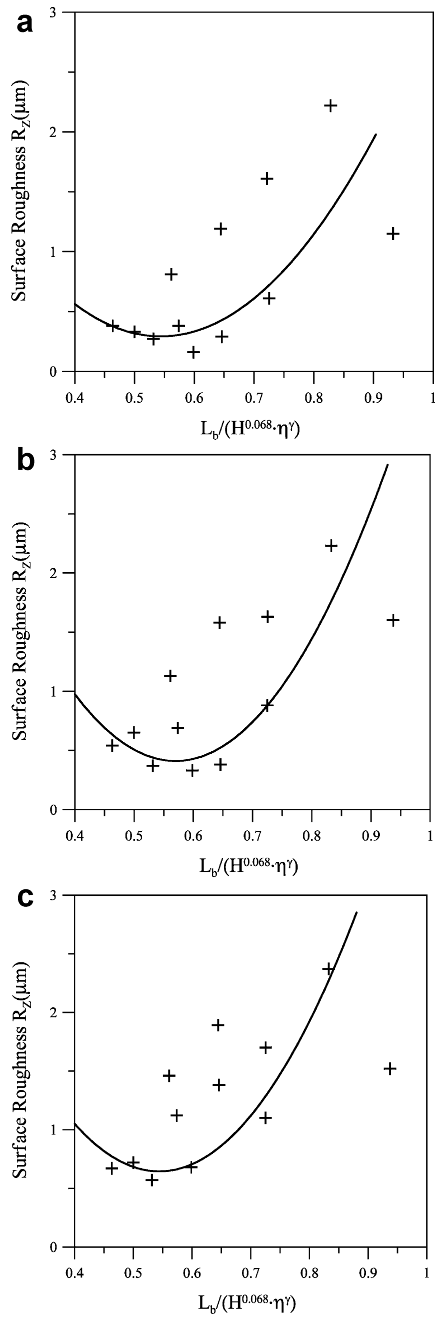

Fig. 4a–c Relationship between surface roughness and burnishing parameter with heavy-duty motor oil (SAE 40) **a** feed = 0.032 mm/rev **b** feed = 0.127 mm/rev **c** feed = 0.506 mm/rev

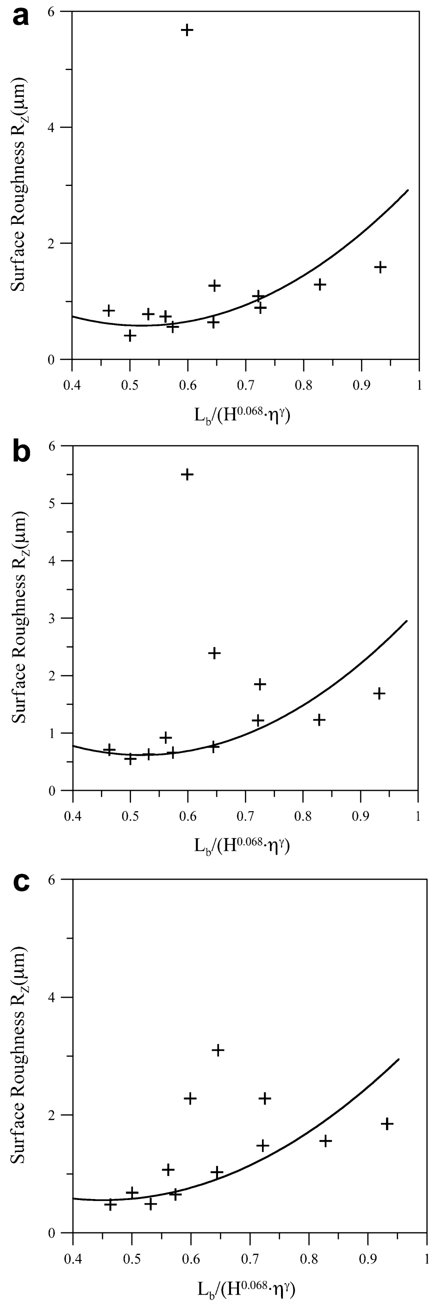

Fig. 5a–c Relationship between surface roughness and burnishing parameter with water-miscible cutting fluids **a** feed = 0.032 mm/rev **b** feed = 0.127 mm/rev **c** feed = 0.506 mm/rev

pressure in each condition. When water-miscible cutting fluids were used as the lubricant, the best-burnished surface was obtained at 2.11 GPa in each burnishing condition, as shown in Table 3. Additionally, adhesive wear occurred at the maximum contact pressure (2.36 GPa) when water-miscible cutting fluids were used as the lubricant, and the wear behaviour increased the surface roughness, as shown in Fig. 3. According to Eq. 2 and the results of the burnishing experiments, this investigation defines the burnishing factor as follows:

$$L_b = \left(\frac{H}{P_{\max}}\right)^{0.068} (V)^{0.073} \eta^{\gamma} \quad (4)$$

Figures 4 and 5 show the use of the experimental results and the burnishing factor L_b to establish the relationship between surface roughness and burnishing factor with different lubricants. The figures indicate that a suitable burnishing factor is required to minimise burnished surface roughness. This suitable burnishing factor can be obtained by adjusting the burnishing pressure, speed, lubricant, and so on. The relationship between surface roughness and burnishing factor in Figs. 4 and 5 is analogous to a Stribeck curve. In the lower burnishing factor region, there is high probability of the occurrence of adhesive wear that reduces the surface quality. On the other hand, in the higher burnishing factor region, elastohydrodynamic (even hydrodynamic) will occur between tool and workpiece during the burnishing process, which results in the improvement in surface roughness being imperceptible.

5 Conclusion

Microscope analysis of asperity deformation during burnishing and experimental results confirms the relationship between the surface qualities of a burnished specimen and the burnishing factor. This concept can explain the phenomenon of different burnishing pressures obtaining the same burnished surface roughness given an identical burnishing factor. Adhesive wear will occur when the burnishing factor is below some critical value. The surface roughness of the burnished specimen will improve slightly when a burnishing factor exceeds some critical value. The optimal burnishing factor, which corresponds to the minimum surface roughness of the burnished workpiece, can be obtained by adjusting the burnishing speed, pressure, lubricant, and so on. The concept of burnishing factor allows increased flexibility in adjusting burnishing parameters to obtain a high quality burnished surface.

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