Surface & Coatings Technology 285 (2016) 171–178

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Toward control of subsurface strain accumulation in nanostructuring burnishing on thermostrengthened steel

V.P. Kuznetsov [a,b], I.Yu. Smolin [c,d], A.I. Dmitriev [b,c,d,*], S.Yu. Tarasov [b,d], V.G. Gorgots [e]

[a] Ural Federal University, Ekaterinburg, Russia
[b] National Research Tomsk Polytechnical University, Tomsk, Russia
[c] National Research Tomsk State University, Tomsk, Russia
[d] Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia
[e] Kurgan State University, Kurgan, Russia

ARTICLE INFO

Article history:
Received 16 September 2015
Revised 2 November 2015
Accepted in revised form 23 November 2015
Available online 29 November 2015

Keywords:
Nanostructure
Burnishing
Control parameters
Modeling
Severe plastic deformation

ABSTRACT

A new process known as nanostructuring burnishing has been developed earlier for improving surface quality and physico-mechanical characteristics of a component by nanostructuring the subsurface layer microstructure. At that the surface modification is controlled by numerous parameters like loading force, friction coefficient, tool's tip radius, strain rate, and number of tool passes. Each of the above-mentioned process parameters has its own specific contribution to the severe plastic strain-induced structural evolution. In this paper we determine two basic integral parameters which would allow controlling the total process of strain accumulation as well as the surface quality obtained. These parameters are friction force and loading repetition. Results are verified by physical modeling by the example of HRC55 20Cr4 steel samples.

1. Introduction

Surface finishing treatments based on subsurface severe plastic deformation (SSPD) are widely known and used. Burnishing is one of them intended for improving a quality of high-precision metallic components with the use of metal-cutting equipment. As shown by many researchers, for example, by H.Y. Luo, M. Nemat, M. Korzynski, S. Swirad, H. Hamadache, F.J. Shiou, L.N. Lopez de Lacalle, F. Mohammadi and others [1–13] the advantages of such a treatment include size precision, reduced roughness, and higher surface layer microhardness combined with the high-level compression residual stresses. By controlling the loading parameters one may tilt the balance between smoothing and hardening effects of burnishing to the desired side. The use of burnishing as a cold working treatment is limited by the effect of overloading and loss of ductility.

A novel approach to improving the service quality of working metal surfaces is based on developing an SSPD treatment known as nanostructuring burnishing [14–17]. Such a treatment allows improving the service life of components used in bore-hole oil pumps.

The effect of improving both physico-mechanical and service characteristics of metallic materials after burnishing is related to the subsurface strain-induced grain refining and work hardening. In practice it is important to provide the optimal value ranges of the nanostructuring burnishing parameters such as contact stress, friction force and number of tool passes which allow avoiding the overstraining of the material elementary volumes. This task can be successfully resolved using a combined approach based on experimental studies and/or numerical modeling. For example, the effect of normal force in burnishing on the workpiece's roughness Ra_{in} and physico-mechanical properties of the material has been studied elsewhere [2,6,18–23]. Let us dwell on these references and discuss the results obtained.

Recent investigations of the burnishing mechanics with an aim to establish a relationship between the friction force level and subsurface layer stress–strain state are infrequent and devoted either to studying the effect of the friction coefficient on the leading bulge evolution, [14] or the effect of feed on microhardness [1,2,6,21]. The important issues relating to a relationship between the loading parameters and the leading bulge evolution, strain accumulation as well as structure and physico-mechanical characteristics of the burnished metal are not given much attention neither theoretically nor experimentally. For example, it is implied that speed of burnishing determines the strain rate in the subsurface of the workpiece. However, the high-rate deformation in cold working is accompanied by the release of heat which has no time enough to completely dissipate into the environment. This extra heat may cause thermal softening of the cold-worked structure especially in combination with high burnishing speeds [2,6].

Numerical approach to studying the basic problems of burnishing was characterized, until quite recently, by either static or quasistatic

* Corresponding author at: National Research Tomsk Polytechnical University, Tomsk, Russia.
E-mail address: dmitr@usgroups.com (A.I. Dmitriev).

http://dx.doi.org/10.1016/j.surfcoat.2015.11.045
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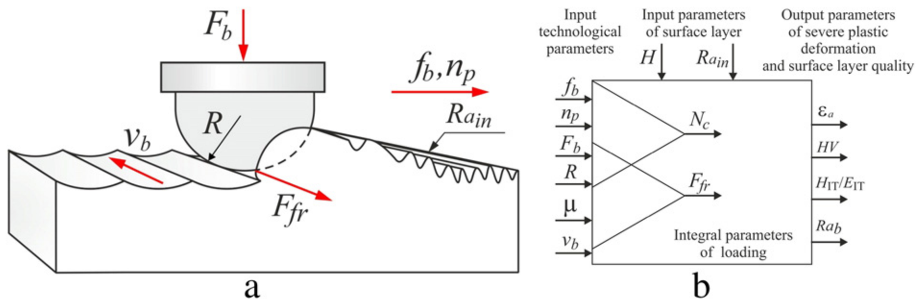

Fig. 1. Schematics of the nanostructuring burnishing process (a) and the process control chart (b). R is the indenter's radius; Ra_{in} is the initial roughness; f_b is the tool feed per one rotation of workpiece; n_p is the tool pass number; F_b is the burnishing force; μ is the coefficient of friction between tool's tip and workpiece; v_b is the burnishing speed; H is the workpiece's hardness; N_c is the loading repetition factor for elementary volume; F_{fr} is the force of friction; ε_a is the accumulated strain; HV is the microhardness; H_{IT}/E_{IT} is the specific hardness parameter; Ra_b is the resulting roughness.

FE problem formulation with respect to only subsurface work hardening [21,24]. In that vein, the interrelation between the basic process parameters and stress state developed in the contact zone still remains to be poorly understood.

The authors [14,17] reported on another approach to the numerical analysis of the strain and stress dynamics of nanostructuring burnishing based on using a constant burnishing force and explicit time integration scheme. The stress–strain state formed in the subsurface of the material after one-time burnishing has been studied using the ANSYS/LS-DYNA FE software [14] within the framework of 2D problem formulation and plane-strain condition of the subsurface layer in heat-treated cemented 20Cr4 steel (HRC55). The influence of both burnishing force and friction coefficient on the specificity of stress distribution and the geometry of the leading bulge has been elucidated. It was shown that for high values of both burnishing force and friction coefficient the stress state in the leading bulge is similar to that of observed under uniaxial compression loading. Also the stress state in the rear zone behind the indenter is close to that of uniaxial tension. The shear stress of alternating sign is found in the lower-lying layers. Such a stress distribution pattern may facilitate rotation-shear mode of deformation and thus to provide strain-induced grain refinement in the subsurface layers.

One of the main tasks in studying the subsurface stress–strain state dynamics of burnishing is to predict the plastic strain level achieved in a single cycle of loading. Following the dynamics of stress accumulation one can see that high, almost 100% strain is achieved and accumulated in the subsurface up to 75 mm thickness layer of material as being induced by the moving indenter [14]. Also this reference shows that for identical burnishing conditions strain that high may rapidly decrease to 10% at the distance 500 mm below the surface.

Summarizing the above results, the authors suggest that effective control of stress–strain conditions for cold working grain refinement can be achieved by changing both the normal force and coefficient of friction between the indenter and the workpiece. The interplay between the two parameters determines the stress state, leading bulge geometry, and plastic strain accumulation during one-time loading as resulted from FE modeling. At the same time the effect of load repetition is an important factor whose studying is hardly possible with the FE modeling and, therefore, has to be carried out experimentally.

So the objective of this study is to reveal and substantiate the nanostructuring burnishing controlling parameters basing both upon previous numerical FE modeling results and presented here experimental results.

2. Controlling process parameters

Substantiation of the process controlling parameters to be utilized for burnishing the engineering materials is determined by all limiting conditions inherent in the SSPD methods as well as by theoretical and practical background relating to cold work hardening the engineering materials. Analyzing the SSPD methods, one can formulate the conditions necessary for the formation of ultrafine and nanosized grain subsurface structures as applied to nanostructuring burnishing.

1. Intensive compression and repetitive simple shear loading [25];
2. rotational plasticity and strain localization [26];
3. nonmonotonicity of deformation and accumulated strain degree above 2 [27]; and
4. maintaining subsurface layer temperature in the strain zone below the shear instability and recrystallization threshold [16].

The nanostructuring burnishing parameters and its control chart with corresponding input and output process parameters are shown in Fig. 1a, b.

Normal load force F_b and friction force $F_{fr} = F_b\mu$ govern the intensity of compression and simple shear deformation, respectively. The friction force is considered as an important integral parameter of loading which serves to determine the intensity of strain-induced structural evolution in the subsurface layer of the workpiece.

Earlier it was shown for sliding friction conditions [26] that maximum plastic strain is achieved at some distance below the surface. This distance increases when the friction force is decreased so that the maximum shear strain is found deep inside the workpiece thus reducing the efficiency of cold work nanostructuring [28]. Such a situation is known to occur in the course of either roll burnishing or peening. On another hand, the high shear strain resulted from high friction may lead to the subsurface deterioration by fracture [1]. In other words, friction force has great effect of the strain and therefore is assumed to be the first integral process controlling parameter (Fig. 1b).

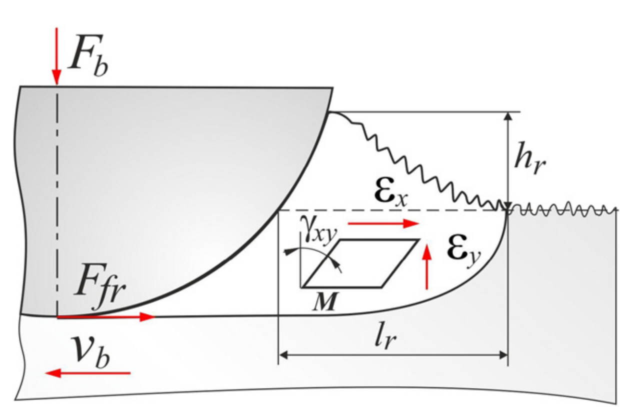

Fig. 2. The deformation parameters acting on the elementary volume M and the leading bulge geometry.