Influence of Roller Burnishing Parameters on Depletion of Plasticity Reserve

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Abstract. Roller burnishing process considerably increases surface quality and service life of machine parts. Efficiency of roller burnishing rises greatly when technological inheritance (TI) is taken into account. Research results of degree of plasticity reserve depletion (DPRD) while roller burnishing are presented. Results obtained made it possible to establish mechanisms of strain accumulation and plasticity reserve depletion according to roller burnishing parameters.

Introduction

Roller burnishing process is one of the most effective ways of work hardening. Scientific studies conducted until date indicate that parameters of roller burnishing properly assigned result in increasing fatigue resistance and service life of machine parts.

Processes of machining feature complex stress distribution and strain accumulation in surface layer. A large number of phenomena on tool-workpiece contact area that one should take into consideration restrain developing an all-purpose model of properties forming. At present, there are considerable quantity of studies that covers mechanics of machining [1-4].

F. Mohammadi, R. Sedaghati and A. Bonakdar developed a high fidelity 3D nonlinear finite element model (FEM) based on the isotropic hardening behavior to simulate low plasticity burnishing of titanium alloy [5]. In that model, the material properties not only depend on the strain, but also depend on the temperature and strain rate. As a result, the profitable compressive residual stress distribution in surface layer has been achieved.

I. Smolin, V. Kuznetsov, A. Dmitriev by using finite element method (FEM) resolved the problem relating stress-strain distribution while diamond burnishing. They concluded that under certain conditions nanostructure formation in superficial layer is possible [6]. N. Chowdhury, A. Patwari, T. Rahman, S. Mostafa obtained analytical solution of elastic stress distribution in the vicinity of the rolling tool while roller burnishing [7].

F. Haji Aboutalebi and A. Banihashemi estimated the practical validation of Hooputra’s ductile damage (HDD) criterion. The mentioned criterion is based on Kolmogorov’s mathematical model and assumes that the equivalent plastic strain at the onset of damage is a function of stress triaxiality and strain rate [8]. The authors believe that HDD is a robust criterion for prediction of failure in ductile metals and that its parameters can be easily obtained from the forming limit diagram (FLD). Other damage criteria were also presented in the conditions of plastic deforming [9, 10].

A. Mahato, Y. Guo1, H. Yeung and S. Chandrasekar investigated metal surface flow in severe plastic deformation (SPD) by sliding using high-speed imaging [11]. The authors derived metal flow...
field and distribution of accumulated strain by the depth of surface layer. Yung-Chang Yen by using 2D and 3D modelling of ball burnishing process calculated strains in the surface layer and estimated surface quality parameters [12].

In up-to-date conditions, it is of great importance to numerically estimate accumulation of strain and forming of surface layer parameters from the attitude of technological inheritance (TI). A large number of works conducted until date indicate that above-mentioned approach can be implemented on the basis of TI mechanics [13]. The theory of quality TI at machining stages is based on the fundamental phenomenological model of continuous surface layer formation exposed to surface plastic deformation. Key mechanical parameters are degree of shear deformation $\Lambda$, indicator of stress state $I$, degree of plasticity reserve depletion (DPRD) $\Psi$.

Roller penetration and movement lead to the occurrence of a deformation site (DS) – local area of plastic flow in surface layer (fig. 1). When the surface layer is exposed to stressing, material particles move into the DS along flow lines 1, 2 and 3, plastic deformation reaches depth $h$. It results into the surface layer characterized with a various depth for shear deformation, plasticity reserve depletion, residual stress profile and surface properties formation. At the next machining operations, strain accumulation occurs with the regard of previously formed surface layer properties.

![Fig. 1. Model of surface layer formation by roller burnishing process: $S$ – feed rate; $R_{cont}$ – roller contour radius](image)

Key feature of TI mechanics is stressing program (SP), which appears as variation of degree of shear deformation $\Lambda$ with indicator of stress state $I$ (fig. 2). LP comprises three steps of quasimonotonous deformation. On each step, continuous strain accumulation takes place in the conditions of changing indicator of stress state. At the key points of SP partial healing of defects and plasticity reserve recovery occur. SP which depends on roller burnishing parameters defines stress-strain state and forms surface layer properties. Under SP action in DS, plasticity reserve depletion takes place, which in turn results in surface layer properties forming.

The degree of plasticity reserve depletion was assessed as follows [14]:
\[
\Psi = \Psi_1 + \Psi_2 = \int_0^\Lambda \left[ n \phi_0 \Lambda_i^{n-1} + \left(1 - \phi_0 \Lambda_p(I) \right) \frac{1}{\Lambda_p(I)} \right] d\Lambda_i, \quad (1)
\]

\(\Psi_1\) – component dependent on flow stress or on accumulated deformation; \(\Psi_2\) – component dependent on metal plasticity with \(I = \text{const}\); \(\Lambda\) and \(\Lambda_p\) – accumulated and maximum permissible degree of shearing deformation with a specific stress state indicator \(I\), \(n\) – strain-hardening coefficient; \(\phi_0\) – coefficient determined by plasticity tests. In the unstrengthened metal \(\Psi = 0\), when plasticity reserve is completely depleted, \(\Psi = 1\).

The advantage of above model is that it reproduces the nature on plastic deformation, which has two features: work hardening, characterized by accumulated strain and defects accumulation, specified by metal plasticity reduction.

**Materials and methods**

In order to validate early obtained analytical models of SP and DPRD calculation experimental researches on roller burnishing of smooth round specimens made of 1045 carbon steel (table 1) were carried out. 1045 steel is one of the most widely used material in modern machine building industry, moreover, its plastic properties is well examined. Rollers were made of 52100 bearing steel.

| | C   | Si  | Mn     | Cr  | S   | P  |
|---|-----|-----|--------|-----|-----|----|
|   | 0.42-0.50 | 0.17-0.37 | 0.50-0.80 | 0.25 | 0.040 | 0.035 |

The burnishing parameters are presented in Table 2.
Table 2: Burnishing parameters

| Specimen number | Number of passes until spalling | Roller diameter $D_R$, mm | Feed rate $S$, mm/rev | Spindle revolution rate $n$, min$^{-1}$ | Roller contour radius $R_{cont}$, mm | Burnishing force $P$, N |
|-----------------|---------------------------------|---------------------------|-----------------------|------------------------------------------|------------------------------------|------------------------|
| 51              | 3                               | 95                        | 0.07                  | 630                                      | 2.5                                | 2500                   |
| 52              | 4                               |                           |                       |                                          | 5.0                                |                        |
| 54              | 3                               | 64                        |                       |                                          | 8.5                                | 2000                   |
| 56              | 4                               |                           |                       |                                          | 5.0                                | 1500                   |
| 57              | 5                               |                           |                       |                                          | 13.5                               | 2000                   |

Specimens’ surface layer was consistently burnished until complete plasticity reserve depletion and bulk material flaking off. Before every next pass, surface layer had fixed value of accumulated strain and DPRD. Burnishing on first pass was carried out almost at full specimen length with DS “freezing”. Burnishing on second pass was performed on already machined surface and so on (fig 3).

Identification of sub-surface cracks, which correspond complete plasticity reserve depletion, was performed using scanning electron microscopy (SEM) on JEOL JSM-7500FA equipment (fig 4).

Geometric parameters of DSs obtained were recognized by using profile recorder “Talysurf 5M” by “Rank Taylor Hobson” company and were used as boundary conditions by FEM simulation. For that purpose, finite elements models of roller and work-piece were created (fig. 5).

Bottom edge of the work-piece was rigidly fixed. The indenter that was an absolutely rigid body was pressed and then shifted along horizontal line by the feed rate. There was no vertical displacement of the indenter. State of plane deformation was assumed. Initial conditions were Young’s modulus $E = 200$ GPa, Poisson’s ratio $\nu = 0.3$, density $\rho = 7800$ kg/m$^3$, friction coefficient on the contact area $f = 0.21$ and flow curve that looked like as follows: $\sigma_i = 360 + 865.6\varepsilon_i^{0.57}$.
Within the framework of above model nodal solution of stress-strain state parameters was obtained by using a special software system [15]. Then parameters of stress-strain state were recomputed along flow lines, general parameters of mechanics and SP were calculated. With knowledge of stress-state index in the selected point of flow line with the use of FLD maximum permissible the degree of shear deformation $\Lambda_p$ was determined. Furthermore, instantaneous value of DPRD in the defined points of flow line was calculated. By adding up instantaneous values of DPRD, we received the accumulated value of DPRD along flow lines.

Analytical calculation of DPRD was carried out at the defined point of flow lines by using previously obtained models of SP steps approximation which may be expressed as:

$$\Lambda = a_{ij}^{SP} \exp\left(b_{ij}^{SP} \right) + c_{ij}^{SP}$$

where $a_{ij}^{SP}, b_{ij}^{SP}, c_{ij}^{SP}$ – factors obtained from experimental researches [16].
Table 3 shows DPRD values, obtained by FEM and by analytical models.

**Table 3: DPRD values obtained by FEM and by analytical models**

| Specimen and pass number | DPRD value, obtained by | DRPD error $\Delta \Psi$, % |
|--------------------------|-------------------------|-----------------------------|
|                          | FEM $\Psi_{FEM}$        | Analytical models $\Psi_{AM}$|
| 51.1                     | 0.403                   | 0.374                       | 7.24 |
| 51.2                     | 0.298                   | 0.322                       | -8.55|
| 51.3                     | 0.256                   | 0.275                       | -7.42|
| 52.1                     | 0.334                   | 0.326                       | 2.53 |
| 52.2                     | 0.238                   | 0.258                       | -3.01|
| 52.3                     | 0.223                   | 0.224                       | -7.37|
| 52.4                     | 0.209                   | 0.203                       | 8.89 |
| 54.1                     | 0.254                   | 0.268                       | -5.51|
| 54.2                     | 0.241                   | 0.233                       | 3.31 |
| 54.3                     | 0.211                   | 0.211                       | -0.06|
| 56.1                     | 0.270                   | 0.261                       | 3.36 |
| 56.2                     | 0.224                   | 0.228                       | -1.94|
| 56.3                     | 0.209                   | 0.205                       | 2.00 |
| 56.4                     | 0.176                   | 0.190                       | -7.68|
| 57.1                     | 0.251                   | 0.248                       | 1.34 |
| 57.2                     | 0.223                   | 0.223                       | -0.13|
| 57.3                     | 0.190                   | 0.205                       | -8.06|
| 57.4                     | 0.181                   | 0.190                       | -5.04|
| 57.5                     | 0.172                   | 0.180                       | -4.68|

In Table 3 $\Delta \Psi$ – DRPD relative error defined as:

$$
\Delta \Psi = \frac{\Psi_{FEM} - \Psi_{AM}}{\Psi_{FEM}} \cdot 100\% .
$$

The variation of DRPD with burnishing force is shown in fig. 6. It is observed that DRPD increases on every pass with increase of the burnishing force. The variation of DRPD with roller contour radius is shown in fig. 7. It is clear that DRPD also increases on every pass with decrease of the roller contour radius. As shown in fig. 8, in every case DRPD increases with decrease of roller contour radius.
Fig. 6. Variation of DPRD with burnishing force (at a constant roller contour radius)

Fig. 7. Variation of DPRD with roller contour radius (at a constant burnishing force)
Results presented in Table 3 show that DPRD values obtained by FEM correlate well with DPRD values obtained by analytical models. DPRP errors are less than 9%.

**Conclusions**

1. Experimental research on roller burnishing of round specimens made of 1045 steel was conducted. Identification of sub-surface cracks was performed by using SEM. Geometric parameters of inherited DS were used as boundary conditions for FEM simulation.
2. Parameters of stress-strain state, SP and DPRD were calculated along flow lines in DSs.
3. It is found that decrease of roller contour radius and increase of burnishing force, which both lead to more heavy plastic flow in DS result in accumulated strain and DPRD growth.
4. Results obtained have shown the possibility of using geometrical parameters of inherited DS for estimation of degree of shear deformation, SP and DPRD of surface layer.

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