The Numerical Analysis of Burnishing Process of Hollow Steel Tubes

Tomasz Dyl

Abstract This paper presents numerical research of burnishing process of hollow steel tubes. The internal surfaces of the tubular elements are treated, among others, by burnishing process. The type of force can be divided into static and dynamic burnishing. The kinematics can be divided into sliding and roller burnishing. Occurrence of moving parts in direct contact with the material qualifies for the group process of burnishing rolling. The sliding burnishing design element property is part of the work surface burnished permanently attached to the handle. Theoretical analysis of the burnishing is carried out numerically. For the calculations were used commercial software Forge based on the finite element method. After burnishing modeling was found intentionally controlled state of stress and strain in the tubular elements to ensure the intended technological quality.

Keywords Numerical analysis · Finite element method · Burnishing process · Steel tubes hollow · State strain · State stress · Forge

1 Introduction

In advanced manufacturing, it is important to obtain good quality products. Therefore, it is used to carry parts up during completion of machinery manufacture. The most common burnishing internal cylindrical surfaces used are in serial productions of machine components. The burnishing process is a finishing machining of hollow tube, having a number of advantages. This treatment increases the dimensional accuracy of holes and the surface roughness parameters decreases, increasing the hardness of the surface layer with formation of compressive residual stresses. It is also important that the burnishing technology allows machining holes with a lack of straightness of the axis. The advantages of burnishing may also be

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considered with high performance and relatively easy technological instrumentation. The tools used for processing by the burnishing special broaches plungers in a variety of shapes and steel balls such as bearing. The beneficial effect of treatment holes burnishing process by the state of the surface layer and the accuracy of the machined holes are obtained for products made of unalloyed steel, steel alloys and stainless steel, copper alloys, and titanium alloys. Burnishing process is most often used for machining of circular cross-section holes with a diameter from a few tenths of millimeter's to about one hundred.

In the papers [1–3] confirmed the usefulness of burnishing process (ballizing process) as a finishing hole machining sliding bearings. It is important that the burnishing technology sets were prepared special burnished elements in the form of beads used as a tool for broaching. At the yield point of the piece-part material, the surface is plastically deformed by the cold flowing of subsurface material. The result is a mirror-like finish and tough, hardened surface. The pressure required for roller burnishing depends on various factors, such as tensile strength of the material, surface toughness before and after burnishing, ductility, shape of the rollers, and diameters.

Developed using artificial neural networks [3] model of stress distribution in the surface layer of workpieces can be used to expand the burnishing process control system, which may advantageously influence the quality of the machined elements used for the machine construction. As part of the many works defining numerical elastoplastic model of plastic surface treatment has been made a number of theoretical analyses using the finite element method to determine the state of stress and strain at the interface of two bodies pressed against [1, 4–8]. On the surface of the contact elements cooperating with one another to determine the status of stress and strain using a Forge MES [9]. This commercial packet Forge is used for simulation different plastic works: rolling, forging and pressing, drawing and other simulated [5, 6, 10–13]. As an innovative application of the program is to use it to burnishing process. Determination of the state of stress in the surface layer is particularly an important issue due to the possibility of the projections at the relevant technological parameters of the mechanical condition of machine components. It takes into account the fact of burnishing force spread out over a contact surface of the spherical tool and the workpiece in the half elastic–plastic. Plastic forming surface modeling consists in determining the impact of the rigid tool predefined curvature of the deformable object, which is the Hertz model, which is a modification of the Bussinesqa model [14, 15].

2 Methodology and Numerical Analysis

The numerical study was conducted for C45 steel samples. The samples were in the form of hollow steel tubes. Internal diameters of samples from each set were made by boring in three dimensions. The largest internal diameter of a set of samples was about 0.1 mm smaller than the diameter of the tool. Two more samples from a given

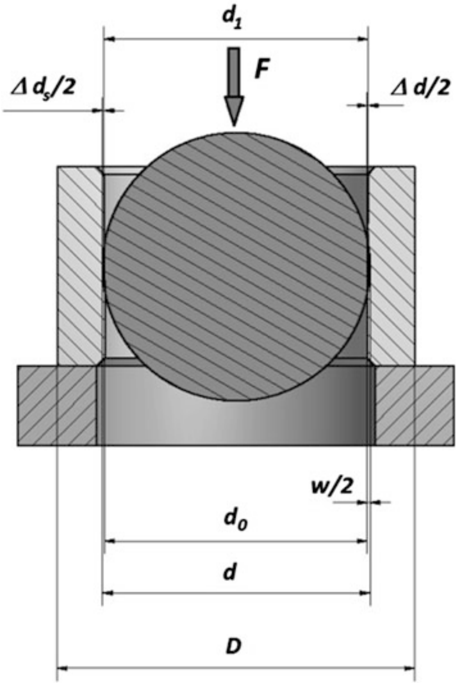

Fig. 1 Schema of burnishing process, D—external diameter tube, d—outer diameter of the ball, d_0—diameter inner tube before burnishing, d_1—diameter inner tube after burnishing, w—reduction ratio, Δd—absolute plastic strain, Δd_s—absolute elastic strain

set of internal diameters were smaller than the ball diameter by 0.2 and 0.3 mm. In Fig. 1 is shown schema burnishing process by ball. Burnishing process is performed using the balls bearing steel 20CrMo4 through the hole. Computer simulations of burnishing were carried out at ambient temperature.

The computer simulations were carried out with C45 steel. The temperature of materials was 20 °C. The external diameter D = 30–45 mm and internal diameter d_0 = 15.56–33.22 mm. The diameter of balls bearing was d = 15.86–33.32 mm. The coefficient of sliding friction of steel on steel is 0.1. The use of a computer program Forge, which is based on the finite element method and has built-in thermo-mechanical models, requires defining the boundary conditions. The boundary conditions are properties of a material, the conditions of friction, kinetic parameters, and thermal properties and tools.

Forge® commercial software uses a model consisting of a finite element mesh, whose base element is a triangle.

The friction forces been model on the basis of the solution Tresca are determined from the equation [9, 10, 16]:

$$\tau = -m\left(\frac{\sigma_0}{\sqrt{3}}\right) \tag{1}$$

where τ—vector of unitary friction forces (MPa), σ_0—base flow stress (MPa), m—friction factor.

The relative plastic deformation for burnishing sliding is expressed by the formula [16]:

$$\varepsilon_n = \frac{d - d_0}{d_0} \cdot 100\ \% \tag{2}$$

where d—outer diameter of the ball, d_0—diameter inner tube before burnishing.

For the computer simulation, the input data are as follows: the initial temperature is the ambient temperature, the heat exchange coefficient between the workpiece and the tool is 3000 W/Kmm^2, the heat exchange coefficient between the material and the air is 100 W/Kmm^2. Due to limitations of the software used movable third element in the form of a thin disk sliding burnishing tubes. The use of moveable tubes on the beads did not affect the accuracy of the calculations and only affect the calculation time by increasing the number of elements in the node which calculations are performed.

Computer simulations were carried out in a three-dimensional reference system. Mechanical state of the deformed material is described by a law Norton–Hoff [9, 10, 16–20]:

$$S_{ij} = 2K_0(\varepsilon + \varepsilon_0)^{n_0} \cdot \mathrm{e}^{(-\beta_0 \cdot T)} \left(\sqrt{3}\,\dot{\varepsilon}_i\right)^{m_0 - 1} \dot{\varepsilon}_{ij} \tag{3}$$

where S_{ij}—stress tensor deviator, $\dot{\varepsilon}_{ij}$—strain rate tensor, $\dot{\varepsilon}_i$—strain rate intensity, ε—strain intensity, ε_0—based strain, T—temperature, K_0, m_0, n_0, β_0—material constants specific to the material considered.

Table 1 shows examples of the geometrical parameters for the steel tubes after burnishing process.

The strain hardening of the material structure of the surface layer is obtained by cold plastic deformation, this improves the fatigue strength. Processing of

Table 1 Geometrical parameters and strain ratio of the tube hollows after burnishing process

No.	D (mm)	d_1 (mm)	d (mm)	d_0 (mm)	w (mm)	ε_n (%)	Δd (mm)	Δd_s (mm)
4511	45	33.28	33.32	33.22	0.1	0.3	0.06	0.04
4512	45	33.29	33.32	33.12	0.2	0.6	0.17	0.03
4513	45	33.29	33.32	33.02	0.3	0.9	0.27	0.03
3521	35	21.97	22.00	21.90	0.1	0.5	0.07	0.03
3522	35	21.97	22.00	21.80	0.2	0.9	0.17	0.03
3523	35	21.97	22.00	21.70	0.3	1.4	0.27	0.03
3031	30	15.84	15.86	15.76	0.1	0.6	0.08	0.02
3032	30	15.82	15.86	15.66	0.2	1.2	0.16	0.04
3033	30	15.83	15.86	15.56	0.3	2.0	0.27	0.03

burnishing provides the creation of a surface layer of large compressive stress, so very often it is observed with the increase of materials treated by burnishing fatigue resistance (surface and volume). Resistance to fatigue is one of the exploitation properties of machines, changing preferably by burnishing. Can be determined based on the relationship between the parameters and the strain and stress state in the surface layer material. It is therefore important to determine the stress and strain state in the tubular elements widely used in the metallurgical industry, machinery, and shipbuilding.

The source of heat evolved in the deformation zone is the work of plastic deformation. In practice, about 10 % of this energy is converted in the area of plastic deformation in the heat. With intensive surface treatment process in the surface layer forming material at the interface with the tool of the present temporary increase in temperature, it is caused not only by the work of deformation, but also by the occurrence of the friction surface of the tool with the workpiece, and the effect on the temperature in the deformation zone of the technological parameters are of the burnishing process.

Figure 2 shows the effective strain and strain rate and stress tensor and pressure distributions substitute for computer simulation of the burnishing ball diameter d = 33.32 mm burnishing reduction ratio 0.3 mm.

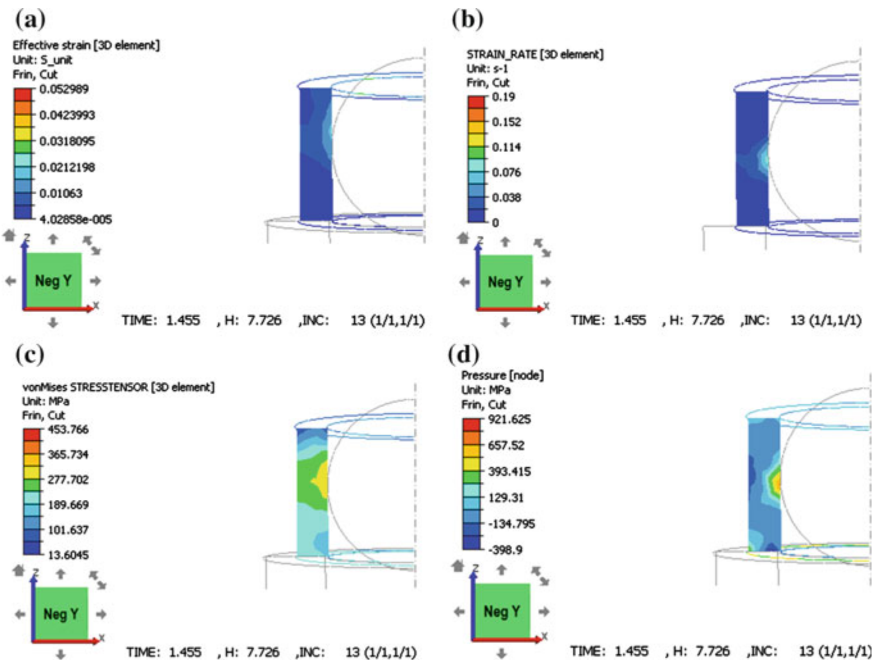

Fig. 2 The distribution of the effective strain (**a**); and strain rate (**b**); and stress tensor (**c**); and pressure (**d**) for ball diameter d = 33.32 mm of the reduction ratio w = 0.3 mm for burnishing

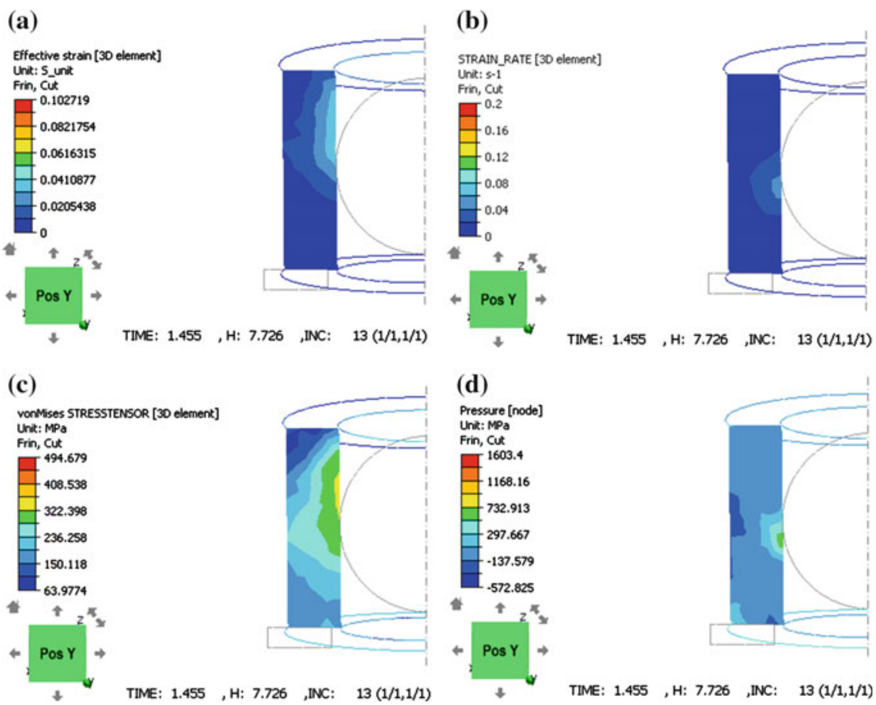

Fig. 3 The distribution of the effective strain (**a**); and strain rate (**b**); and stress tensor (**c**); and pressure (**d**) for ball diameter d = 22.00 mm of the reduction ratio w = 0.3 mm for burnishing

Figure 3 shows the effective strain and strain rate and stress tensor and pressure distributions substitute for computer simulation of the burnishing ball diameter d = 22.00 mm burnishing reduction ratio 0.3 mm.

Figure 4 shows the effective strain and strain rate and stress tensor and pressure distributions substitute for computer simulation of the burnishing ball diameter d = 15.86 mm burnishing reduction ratio 0.3 mm.

Because of nature of the burnishing shown axisymmetric distributions of selected strains and stresses in the middle of the tube hollow on the longitudinal section.

Based on the results shown in Figs. 2, 3 and 4, it can be concluded that the effective strain and strain rate and stress intensity depend on the outer diameter of the ball.

For smaller diameters balls of stress take the greatest value. It can be concluded that the intensity of the deformation in the outer layer of the hollow tube from inside of contact with the ball increases with the reduction ratio. Conversely, the intensity is proportional dependence of the deformation and the diameter of the balls. Similarly it occurs in the event of deformation. For larger values of the diameter of the balls as well as the intensity of deformation strain rate values take smaller and smaller diameter of the balls reach the higher values. This character of stress and

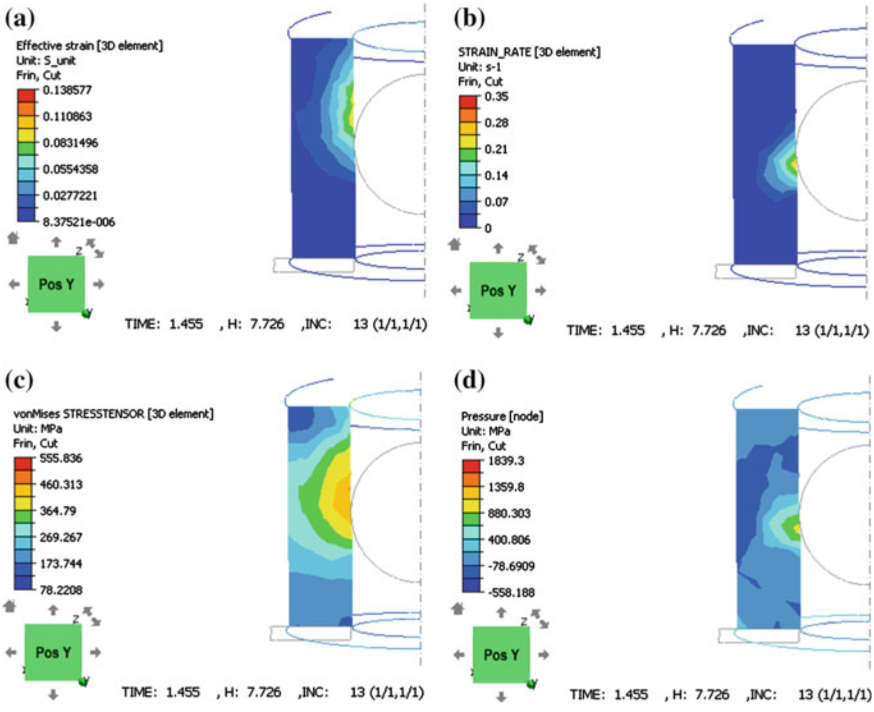

Fig. 4 The distribution of the effective strain (**a**); and strain rate (**b**); and stress tensor (**c**); and pressure (**d**) for ball diameter d = 15.86 mm of the reduction ratio w = 0.3 mm for burnishing

strain distribution is determined by the average stress values increase with decreasing diameter of the balls. This is directly related to the decrease in the surface area of contact deformation element burnishing the inner wall of the hollow tube.

Depending residual stress as a function of: the outer diameter of the ball, absolute and relative plastic deformation for the burnishing set within 50 μm from the machined surface of the tube hollow and is shown in Figs. 5 and 6.

With the increase in the value of the diameter of the ball burnishing strain value decrease. Such nature of the deformation state is directly dependent on the state of stress occurring in the outer layer of the tube hollow subjected to burnishing.

Based on the analysis results shown in Figs. 5 and 6 it can be concluded that the residual stresses are numerically calculated dependent on two variables: the outer diameter of the balls and the predetermined strain for burnishing. It can be concluded that the higher relative plastic deformation and with the increase of the reduction ratio, while reducing the diameter of the ball there is an increase the absolute value of the compressive residual stress in the inner surface layer of the tube hollow.

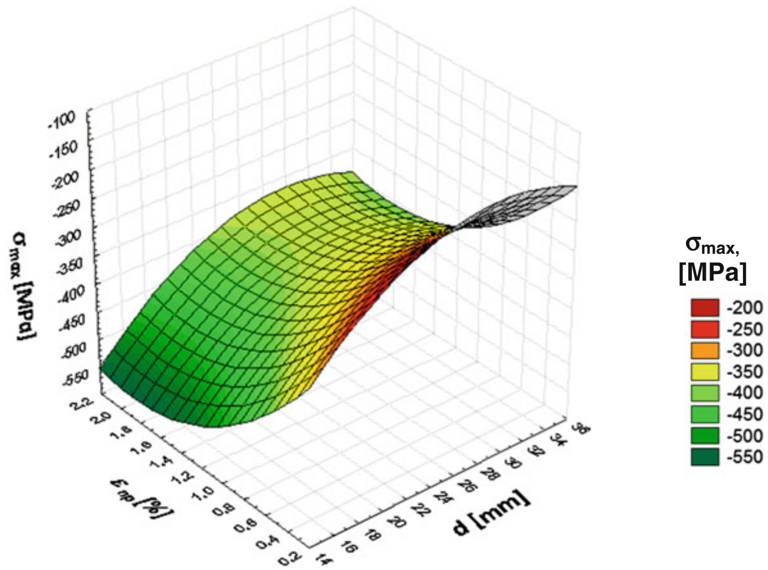

Fig. 5 Residual stress—$\sigma_{\max}$, as a function of d the outer diameter of the ball and ε_{np}—relative plastic deformation for burnishing

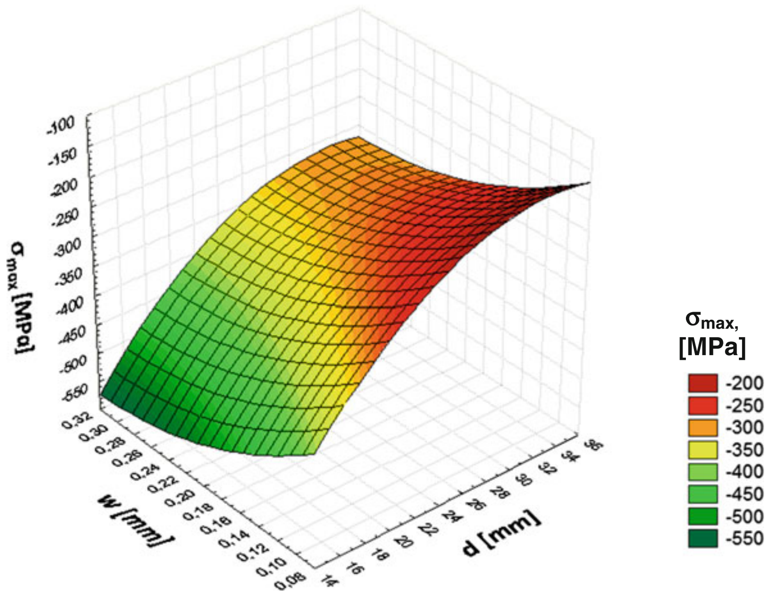

Fig. 6 Residual stress—$\sigma_{\max}$, as a function of d—outer diameter of the ball and w—reduction ratio for burnishing

In order to determine the depth of the zone of plastic deformation used in numerical analysis based on the finite element method. The paper was determined as a numerical solution for contact and deformation of bodies on the basis of the theory of plasticity and elasticity. Based on numerical analysis of the equations for calculating the depth of plastic deformation zone. For the required boundary conditions and specific areas of research, determined on the basis of their own numerical sliding burnishing the relationship between the depth of the zone of plastic deformation and the deformation and reduction ratio shown by the equation:

$$h_{\delta} = 0.756w^{1.667} \tag{4}$$

where h_{δ}—depth of deformation zone, w—reduction ratio.

After burnishing sliding surface layer are compressive residual stress resulting from the increased specific volume of the material in a plastic state. The maximum absolute value stresses occur near the surface subjected to burnishing. The presence of compressive stresses in the surface layer is preferred due to improved performance, especially the increase in fatigue strength of machine parts, but also to tribological wear.

3 Summary

The paper presents the effect of burnishing process on the state of stress and strain of the hollow steel tubes. Burnishing is a technology of surface plastic forming of machine parts. Burnishing is used as a finishing strengthens, and smoothness, can be realized on the universal machine tools and machining centers, effectively replaces the machining operations, such as grinding, reaming, honing, and lapping.

The numerical analysis is determining that the reduction ratio has significantly influenced on the state strain and state stress of the inner tube holes after burnishing process.

An increase in the value of reduction ratio, the value of the effective strain increases. After burnishing simulations can be concluded that the most intense nature of the surface of an elastically deformable material contact with the ball is the state of effective strain and strain rate. The values of the deformation tensor gradient propagate into the material. Examined the cross-section of the tube hollow can be seen that the area is characteristic of the occurrence of deformation tensors maximum value at a certain depth from the surface of the workpiece, but not more like half of the wall thickness of the tubes. After burnishing is constituted compressive residual stresses in the surface layer that result from increased specific volume of the material in a plastic state. The maximum absolute value stresses occur near the surface of the treated burnishing.

After burnishing numerical studies determines the relationship between the depth of the zone of plastic deformation and the deformation and reduction ratio.

After analysing the numerical computer simulations of burnishing can be conclude that can effectively specify state of strain and state of stress required for planning finishing machining abrasive tube for the piece production and small lot production.

It has been determined that it is possible to intentionally form state of stress and strain in the tubular elements intended to provide technological quality while maintaining the required strength and the exploitation properties surface layer of the workpiece.

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