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# Calculating the process of straightening low-stiff cylindrical parts by cross-rolling with smooth plates

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**Abstract.** To restore the shape of curved low-stiff cylindrical parts such as shafts and axles, the process of straightening by transverse bending is considered with subsequent hardening by the method of surface plastic deformation based on the transverse rolling of the cylindrical part with flat plates. The stress states of parts during editing are determined using the Ansys Workbench software package. The results of the distribution of the intensity of operating voltages and residual stresses over the cross section of the cylinder, depending on the absolute compression, are presented. The process in question can be implemented without the use of environmentally hazardous lubricating cooling technological means, which makes it possible to attribute it in the future to one of the types of green mechanical processing technologies. e

## 1. Introduction

Cylindrical parts of low rigidity such as shafts and axles are widely used for the manufacture of various products in the agricultural, mining, automotive, aviation industry and household appliances. Such parts allow not only to transfer power over long distances (within the overall limits of the machine), but also significantly reduce the metal consumption of products. Low-stiff shaft-type parts have one important drawback - this is a distortion of the geometrical shape both during manufacture, assembly, and during operation. Therefore, at all stages of the technological process in the manufacture of non-rigid parts such as shafts and axles with a ratio of length to diameter of more than 10, several editing operations are usually included in the manufacturing and assembly process [1, 2]. e

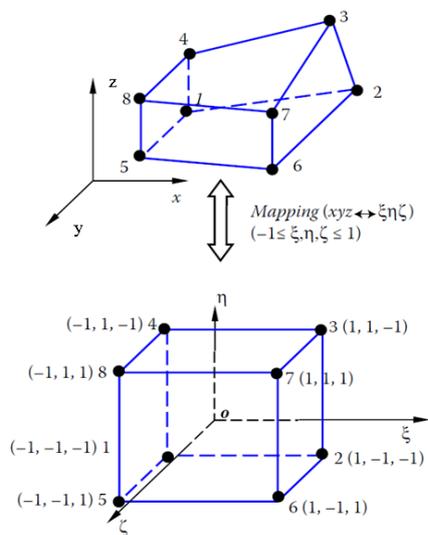
Straightening is the traditional way of restoring the geometric shape of the curved parts. A great contribution to the development of the theory and technology of editing cylindrical products was made by domestic and foreign scientists: Ya.D. Vishnyakov, A.S. Donskov, V.N. Yemelyanov, G.V. Muratkin, I.I. Manilo, N.P. Shchapov, E. Albert, and others. However, the non-uniformity and instability of the stressed state of parts after straightening serves as a limitation for the inclusion of this process in the manufacture of very precise structures. Many ways of editing give a temporary effect or lead to damage to the surface layer, which is unacceptable when the straightness of the finished parts is restored [1-3]. d



The authors have developed a new kinematics of the editing process, which allows to reduce the unevenness of the stress state in the machine parts. As a promising direction, we can consider straightening by transverse bending followed by hardening of the workpiece by means of surface plastic deformation (SPD), based on transverse rolling of the workpiece with flat plates [4, 5]. This effective method is largely free from the above disadvantages. For the practical implementation of the new method of straightening, it became necessary to calculate the working voltages required for straightening parts and residual stresses after lateral straightening. The effect of residual stresses on the quality of products after surface plastic deformation is described in [6].

**2. Calculating of stress-strain state - principles**

The solution of the elastoplastic problem was carried out using the finite element method (FEM). The area under study is a set of finite elements of the form - a hexahedron (figure 1).



**Figure 1.** Mapping an element to the natural coordinate system.

Components of the movements. Offset field in a three-dimensional element using the functions of the form  $N_i$  [7, 8, 9]:

$$u = \sum_{i=1}^8 N_i u_i, \quad v = \sum_{i=1}^8 N_i v_i, \quad w = \sum_{i=1}^8 N_i w_i, \tag{1}$$

in which  $u_i$ ,  $v_i$  and  $w_i$  are nodal values of the displacement on the element, and  $N$  is the number of nodes on that element. Formula (1) in matrix form is:

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_{3 \times 1} = \begin{bmatrix} N_1 & 0 & 0 & N_2 & 0 & 0 & \dots \\ 0 & N_1 & 0 & 0 & N_2 & 0 & \dots \\ 0 & 0 & N_1 & 0 & 0 & N_2 & \dots \end{bmatrix}_{3 \times 24} \begin{Bmatrix} u_1 \\ v_1 \\ w_1 \\ u_2 \\ v_2 \\ w_2 \\ \vdots \end{Bmatrix}_{24 \times 1}. \tag{2}$$

Matrix (2) can be represented as:

$$u = N \cdot d.$$

Shape Functions:

$$N_1(\xi, \eta, \zeta) = \frac{1}{8}(1 - \xi)(1 - \eta)(1 - \zeta),$$

$$\begin{aligned}
 N_2(\xi, \eta, \zeta) &= \frac{1}{8}(1 + \xi)(1 - \eta)(1 - \zeta), \\
 N_3(\xi, \eta, \zeta) &= \frac{1}{8}(1 + \xi)(1 + \eta)(1 - \zeta), \\
 &\vdots \\
 N_8(\xi, \eta, \zeta) &= \frac{1}{8}(1 - \xi)(1 + \eta)(1 + \zeta),
 \end{aligned}$$

Note that we have the following relations for the shape functions:

$$\begin{aligned}
 N_i(\xi_i, \eta_i, \zeta_i) &= \delta_{ij}, \quad i, j = 1, 2, \dots, 8. \\
 \sum_{i=1}^8 N_i(\xi_i, \eta_i, \zeta_i) &= 1
 \end{aligned}$$

Coordinate Transformation (Mapping):

$$x = \sum_{i=1}^8 N_i x_i, \quad y = \sum_{i=1}^8 N_i y_i, \quad z = \sum_{i=1}^8 N_i z_i, \tag{3}$$

### 3. Calculating of stress-strain state - principles

That is, for the geometry of the element, the same form functions are used as for moving the field. This kind of element is called an isoparametric element. The transformation between  $(\xi, \eta, \zeta)$  and  $(x, y, z)$  described by equation (3) is called the isoparametric map (see figure 1), we have the following equations [9, 10, 11]:

$$\begin{Bmatrix} \frac{\partial u}{\partial \xi} \\ \frac{\partial u}{\partial \eta} \\ \frac{\partial u}{\partial \zeta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} & \frac{\partial z}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} & \frac{\partial z}{\partial \eta} \\ \frac{\partial x}{\partial \zeta} & \frac{\partial y}{\partial \zeta} & \frac{\partial z}{\partial \zeta} \end{bmatrix} \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial u}{\partial y} \\ \frac{\partial u}{\partial z} \end{Bmatrix} = J \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial u}{\partial y} \\ \frac{\partial u}{\partial z} \end{Bmatrix},$$

where J is the Jacobian Matrix [12, 13, 14].

Inverting this relation, we have:

$$\begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial u}{\partial y} \\ \frac{\partial u}{\partial z} \end{Bmatrix} = J^{-1} \begin{Bmatrix} \frac{\partial u}{\partial \xi} \\ \frac{\partial u}{\partial \eta} \\ \frac{\partial u}{\partial \zeta} \end{Bmatrix}, \tag{4}$$

with  $\frac{\partial u}{\partial \xi} = \sum_{i=1}^8 \frac{\partial N_i}{\partial \xi} u_i$  and so on, similarly for v and w. These relations lead to the following expression for the strain:

$$\varepsilon = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial w}{\partial z} \\ \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \\ \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \end{Bmatrix}. \tag{5}$$

Using the relationships given in equations (2), (4) and (5), we can derive the deformation vector to obtain :

$$\varepsilon = Bd,$$

in which B is the matrix connecting the nodal displacement vector d with the deformation vector  $\varepsilon$ . Strain energy is evaluated as:

$$U = \frac{1}{2} \int_V \sigma^T \varepsilon dV = \frac{1}{2} \int_V (E\varepsilon)^T \varepsilon dV = \frac{1}{2} \int_V \varepsilon^T E \varepsilon dV = \frac{1}{2} d^T \left[ \int_V B^T E B dV \right] d.$$

That is, the element stiffness matrix is

$$k = \int_V B^T E B dV.$$

In  $\xi\eta\zeta$  coordinates:

$$dV = (\det J) d\xi d\eta d\zeta.$$

Therefore,

$$k = \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 B^T E B (\det J) d\xi d\eta d\zeta.$$

It is easy to verify that the dimensions of this stiffness matrix are  $24 \times 24$ .

#### 4. Conclusions

To compute the stresses within an element, one uses the following relation once the nodal displacement vector is known for that element:

$$\sigma = E\varepsilon = EBd.$$

Stresses are evaluated at selected points (Gaussian points or nodes) on each element. The voltage values at the nodes are often intermittent and less accurate. Averaging stresses from surrounding elements around a node is often used to smooth the results of the stress field.

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