Simulation of thin-walled workpieces ends expanding for pipelines making

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Abstract. Experience of pipelines operation shows that their failures are often connected with thinning of walls in bending areas and with abrupt transition from one wall diameter to another. It is possible to make this transition smoother by using of connecting pipes with variable diameter. Such parts can be obtained by forming process of expanding. In this paper, the process of cold expanding of the end of thin-walled tubular workpiece, which is made from aluminium alloy AMg6M, against hard die, is investigated by finite-element method in ANSYS. It is used the saddle-shaped die, which makes it enable to produce connecting branches similar to the form of two joined pipes with specified blending radius. It has been investigated maximal and residual stresses in deformed part, as well as wall thinning. This stresses do not exceed tensile strength of the material. Therefore, it has been proved the possibility to obtain connecting pipes per one processing step, which do not require subsequent mechanical treatment. Wall thinning corresponds to technological norms.

1. Introduction
Metal forming is the process of parts manufacturing by force action on initial workpiece. This process is one of the main methods of parts manufacturing in mechanical engineering because of its relatively low cost and materials consumption, as well as relatively high efficiency.

Pipelines are one of the most important structural elements in mechanical engineering. They work under complex loading conditions. Pipelines are subjected to high pressure, pulsating loads and hydraulic shocks. Therefore, they have to meet the requirements of physical and mechanical properties of materials, surface finish, distortion of section form, and pipe wall thinning.

Working efficiency of pipelines can be reduced in consequence of excessive circular deviation and waviness of walls, that is, objectionable phenomena which accompany the process of workpiece deformation. Experience of operation shows that pipelines service failures are in most cases related to thinning of walls in bending points and with abrupt transition from one wall diameter to another [1]. One of the ways to make this transition smoother is using of connecting pipes, one of the ends of which has greater size than the other. Such parts can be obtained by forming process of expanding [2-8].

Defects of welding bead at the joints of the main and branch pipes can be one more significant problem during pipelines production. It may occur that the electrode metal penetrates into the pipeline and reduces the cross-sectional area of the branch pipe (Figure 1a). One of the ways to overcome this problem is also the creation of connecting pipes, in which one end is previously subjected to the forming process of expanding. In this case, the welding bead is moved to the zone of the header pipe, and even in the event of defect appearance, the area of its cross-section varies insignificantly (Figure 1b).
Figure 1. Probable defect of pipeline (reduction of cross-sectional area of a branch pipe) and method of its elimination: welding bead in the area of branch pipe (a) and in the area of header pipe (b); advisable shape of branch pipe (c).

However, it is necessary to take into account that weld width is approximately 1 mm. Therefore it is advisable that after expanding process the shape of branch pipe as much as possible replicates the form of two joined pipes with specified blending radius. With this purpose in mind, in present work the process of connecting pipe forming by expanding of cylindrical tubular workpiece is investigated by FEM simulation in ANSYS Workbench. It is used the saddle-shaped die, which shape makes it enable to produce connecting branches similar to ones in Figure 1c. Residual stresses and elastic strains, plastic strains boundary and part walls thinning are determined.

2. Geometrical model and finite element model
Geometrical model of the die and sectional view of tubular workpiece executed in ANSYS DesignModeler is shown in Figure 2a. Workpiece height \( l = 30 \) mm, outer diameter \( d = 8 \) mm, wall thickness \( h = 0.8 \) mm. This shape of the die was obtained as union of circular cylinder, corresponding to inner volume of branch pipe, and a part of circular cylinder, corresponding to inner volume of header pipe. Axes of cylinders intersect orthogonally, and their surfaces are blended. Die dimensions are presented on section planes \( OXY \) and \( OYZ \) in Figures 2b and 2c. Blending radius \( R \) is varied.

Finite element model is shown in Figure 4. Coordinate planes \( OXY \) and \( OYZ \) are the planes of symmetry, therefore, with the purpose of problem size reduction, calculations have been carried out for a quarter of geometrical model. Die is considered as perfectly rigid body, and so only its surface contacting with workpiece is of interest. Finite element model of the die contains one element by thickness. Its boundary conditions correspond to rigid attachment.

Figure 2. Geometrical model of tubular workpiece (in section) and die (a); sections of the die by planes \( OXY \) (b) and \( OYZ \) (c).
Figure 3. Finite-element model of tubular workpiece (a) and die (b).

It should be noted that previously mentioned assumptions has no effect on the results accuracy. For comparison purposes, it has been solved the problem where the die was considered as elastic-plastic solid presented in Figure 3, which is made from steel. Boundary conditions consisted in prohibition of vertical displacement for lower surface. Ultimately, deformations of the die proved to be negligible quantity. That is why it was decided not to take them into account for calculations time reducing.

After discretization the die is composed of 1200 higher order 3-D 20-node solid elements SOLID186. Tube wall is formed of 4000 elements SOLID186. It has been taken 4 elements by thickness. Coefficient of dry friction on contact surfaces is taken equal to 0.1. Contact and target surfaces are represented by elements CONTA174 and CONTA170, respectively.

Upper end of the tube is subjected to downward vertical displacement. Displacement value depends on blending radius: $s = R\pi/2$.

The problem has been solved in ANSYS Static Structural module. Stress-strain state is described with the use of elastoplastic model with linear isotropic hardening. Total strains are divided into reversible and irreversible components in accordance with relationship

$$\varepsilon_0 = \varepsilon_0^r + \varepsilon_0^\iota.$$

Elastic strains are connected with stresses by generalized Hooke’s Law

$$\sigma_{ij} = \frac{E}{1+v} \varepsilon_{ij}^r + \frac{E\nu}{(1+v)(1-2\nu)} \varepsilon_{ij}^\iota \delta_{ij},$$

where $\sigma_{ij}$ and $\varepsilon_{ij}^r$ are components of stress tensor and elastic strain tensor, $E$ is Young’s modulus, $\nu$ is Poisson’s ratio, and $\delta_{ij}$ is Kronecker delta. The von Mises yield criterion has been used for irreversible deformations description. It can be written in terms of the principal stresses as follows:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = \sigma_\tau^2.$$

Here $\sigma_\tau$ is the tensile yield stress.

The tube is considered to be made from aluminium alloy AMg6M. Its physical-mechanical properties are given in Table 1.
Table 1. Physical-mechanical properties of aluminium alloy AMg6M [10].

| Parameter               | Notation | Value  | Unit of measure |
|-------------------------|----------|--------|-----------------|
| Young's modulus         | $E$      | $7.1 \cdot 10^4$ | MPa             |
| Poisson's ratio         | $\nu$    | 0.33   |                  |
| Tensile yield stress    | $\sigma_T$ | 170    | MPa             |
| Hardening modulus       | $E_T$    | 71     | MPa             |
| Ultimate tensile strength | $\sigma_B$ | 340    | MPa             |

3. Results and discussions

The calculations have been made for four different blending radii from 1.5 mm to 3 mm in increments of 0.5 mm. In Figure 4, there are contour plots of von Mises equivalent stress $\sigma_{eqv}$ distributions at the moments of maximum vertical displacement of the tube:

\[
\sigma_{eqv} = \frac{1}{2} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right]^{1/2}
\]

Figure 4. Equivalent von Mises stress distribution at the moment of maximal vertical displacement in deformed parts with blending radii $R=1.5$ mm (a), $R=2.0$ mm (b), $R=2.5$ mm (c), $R=3.0$ mm (d).

Residual stresses for the same geometrical parameters, obtained after removing of tool, are shown in Figure 5. One can see from the Figures 4 and 5 that stresses $\sigma_{eqv}$ do not exceed tensile strength $\sigma_B$. This means that mechanical strength of the part is ensured.

Figure 6 illustrates residual equivalent von Mises plastic strain

\[
\varepsilon_{eqv}^p = \frac{1}{1 + \nu} \left[ \left( \varepsilon_x^p - \varepsilon_y^p \right)^2 + \left( \varepsilon_y^p - \varepsilon_z^p \right)^2 + \left( \varepsilon_z^p - \varepsilon_x^p \right)^2 \right]^{1/2}
\]

Hence, it can be determined the boundary of plastic deformations.

It has been investigated tube wall thinning. In Figure 7 it is demonstrated the thinning of bottom 7.5 mm length of deformed tubular part. Blue, red and green lines correspond to wall thinning in $OYZ$ plane, $OXY$ plane, and at the angle $45^\circ$ between them, respectively. Maximal thinning does not exceed 32%.
Figure 5. Residual equivalent von Mises stress distribution after pressing tool removing in deformed parts with blending radii $R=1.5$ mm (a), $R=2.0$ mm (b), $R=2.5$ mm (c), $R=3.0$ mm (d).

Figure 6. Residual equivalent von Mises plastic strain distribution after pressing tool removing in deformed parts with blending radii $R=1.5$ mm (a), $R=2.0$ mm (b), $R=2.5$ mm (c), $R=3.0$ mm (d).

4. Conclusion
Carried out calculations and the results of simulation show that it is possible to produce connecting pipes from tubular workpieces, which are made from aluminium alloy AMg6M, by compressing a thin-walled tube against saddle-shaped die. Stresses in deformed part do not exceed tensile strength. The gap between connecting pipe and the wall of header pipe is less than 0.5 mm and therefore it can be spanned during welding. At the same time, if mentioned above defect occurs it cannot significantly reduce cross-sectional area of a branch pipe. Thus, it has been proved the possibility to obtain connecting pipes per one processing step, which do not require subsequent mechanical treatment.
Figure 7. Wall thickness of deformed parts with blending radii
$R=1.5$ mm (a), $R=2.0$ mm (b), $R=2.5$ mm (c), $R=3.0$ mm (d).

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