Cold deformation of non-circular drill pipes

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Abstract. In this paper, the pipe billet dimensions are determined according to the required kelly configuration. A finite element model of the deformation center at drawing junctions is created. Based on the stress-strain calculations, the following invariants are determined: hydrostatic pressure, load, and degree of shear strain. The metal damage extent is determined and proved to be reducible by performing the two-pass drawing. It is shown that the ‘pendulum’ heat treatment provides for complete healing of the metal defects caused by plastic deformation. As a result, a technology of producing high quality kellys is proposed.

1. Introduction
Kellys are an integral part of drill strings that are designed to transfer torque to the working tool. They largely determine the penetration efficiency of oil and gas wells. The main part of a kelly is a non-circular thick-walled tubing with an internal channel [1]. The most effective way to produce such tubings is to draw them in a profile die on a moving mandrel. However, to date, there is no theoretical justification for this plastic deformation process. To provide it, a number of problems must be solved, including determination of the billet size and shape, the longitudinal and transverse configuration of the working tool, the number of broaches, extent of the metal damage and its healing capacity under heat treatment.

2. Methods
The analysis has revealed that it is necessary to combine centers of gravity of the billet and the finished profile and to ensure equality of the cross-section drawing of the profile elements [2]. For this purpose, a round or profile billet, similar to a finished profile, can be used. In the current study, a round thick-walled tube was used as a billet. The billet wall diameter and thickness were calculated based on the research described in [3]. Then, the principle of least action was applied. This made it possible to determine the metal flow lines [4, 5] that were approximated using cubic splines [6]. Additionally, equipotential lines were drawn to determine the die output cross-section at transitions [7, 8] (Figure 1).
Figure 1. Finite element model of the deformation center: (a) and (b) are the first and the second deformation passes, respectively.

As a result, a model of producing square pipes in two passes by drawing them on a long moving mandrel was created. The solid model included three bodies: a smooth billet model, a long cylindrical mandrel, and a profile die. To reduce the processing time, we considered the problem from the plane symmetric perspective (1/8 of a full profile). The solid model was exported in the SAT format (developed by Spatial Corp.).

After transfer to the finite element package, the model was split using elements of the tetrahedron type as they are the most suitable for pipes of complex curvilinear shapes. The grid density on contacting surfaces of the mandrel, die, and the pipe billet was additionally increased. This made it possible to determine the finished profile shape and to make the surfaces more ‘smooth’ and transfer them with a better precision, which reduced the probability of errors at modelling of the relative slip on contacting surfaces.

Two sets of contacting surfaces were considered: that of the mandrel with the pipe model inner surface and of the die working surfaces with the pipe outer surface. The coefficient of friction was set...
According to the tabular data taking into account in-situ measurement values. The friction coefficient was adjusted based on actual values of the energy and power parameters (in particular, the drawing force). The mandrel and the pipe movement ranges were set. The die was set to be fixed and nondeformable. The symmetry planes were also specified.

The material properties were set as a multi-linear hardening curve that factored in both elastic and plastic properties of the pipe material. The finite element package allowed for taking into account instantaneous variable properties of the material of different model elements. This made it possible to take into account the elastic effect of individual profile elements after their leaving of the deformation zone, which had a positive impact on the geometric modeling accuracy.

After determining the pipe shape at the first transition, the profile was approximated using arcs and segments. Then, the resulting polyline was used as a basis for modeling geometry of the pipe at the second transition. The transition damage measured at reference points of the profile was summed up to determine the full extent of the metal damage.

The solution was to ensure the intermediate transition rational shape in order to reduce the working tool wear, minimize the pipe material damage (by increasing the deformation fractionality), and produce non-circular pipes meeting the specification requirements. This was achieved due to fuller filling of the profile corners and consequent reduction of the rounding radii at the profile edges.

The application of the finite elements method made it possible to determine all invariants of the metal stressed and deformed conditions and its damage (ω0) at ‘dangerous’ points of the pipe cross-sections at each deformation stage. As known, there exist critical values (ω* and ω**) that should be compared with ω0. Within the range of these critical values, defects caused by plastic deformation are healed differently. Thus, if 0<ω0<ω*, defects are completely healed during further annealing. If ω*<ω0<ω**, only some of the defects are healed [10, 11, 12].

At the first stage, the single-pass drawing was studied. It was found that on the profile edges ω0>ω**, i.e. more than the allowable value. To increase the deformation fractionality and reduce ω0, the two-pass drawing was applied. At the first transition ω0=0.69, at the second - 0.534, which, in total, also exceeded the allowable value. For this reason, in between the passes, the ‘pendulum’ annealing should be applied. It allows to expand the boundaries of reversible damage from 0.37 to 0.5 by increasing the size of the healed defects. The healing value was calculated using the following formula [9]:

$$\Delta \omega = \omega^* + \frac{c_1 - \omega^*}{\omega^{**} - \omega^*} (\omega_0 - \omega^*)$$  (1)

The resulting residual damage for the first pass is ω1=0.14, for the second - ω2=0.126, which is acceptable.

3. Conclusion
It was found that the preferable way of kelly production includes two drawing passes with ‘pendulum’ annealing after each of them.

This method proved to provide the following benefits:

1. Obtaining a precisely shaped profile due to calibration and elimination of temperature distortions during the heat treatment at the last transition.

2. Acceptable values of material damage due to its significant reduction during the heat treatment.

Besides, repetitive nature of the heat treatment makes it possible to control the product properties, e.g. using express methods of the surface hardness measurement, which prevents failures related to mechanical properties.

This approach provided the best results in terms of quality and reliability of finished products.

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