Terotechnology 2017 Materials Research Forum LLC
Materials Research Proceedings **5** (2018) 220-224 doi: http://dx.doi.org/10.21741/9781945291814-39

Distribution of Forces and Analysis of Friction Coefficient during Envelope Rolling of Tapered Tubes

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Keywords: Conical Pipe, Envelope Formation Process

Abstract. Conical pipes belong to a group of economical profiles which find broad application in various metal products. Manufacturing of conical pipes belong to complicated engineering processes, and the existing methods do not allow for the demand for conical pipes to be met– especially the long ones with large crosswise dimensions, e.g. pipes for lamp posts. This situation makes it reasonable to look for new processes with wider engineering possibilities when compared to the existing methods. It seems that the process of conical pipe envelope formation will allow for a wide conical pipes assortment.

Introduction

Laboratory testing of conical pipes formed by means of the envelope rolling method – a test stand. The test stand (Fig. 1) to form conical pipes was installed on a lathe. The stand base, including the device body was screwed down to the lathe slide.

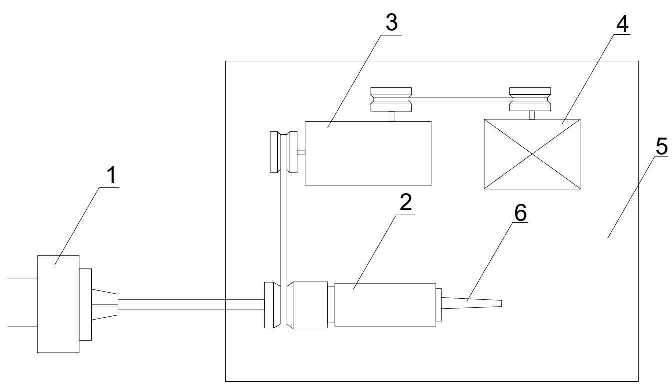

Fig. 1. Diagram of a test stand to roll conical pipes; 1 – lathe slide, 2 – rolling device, 3 – worm gear, 4 – gear drive motor, 5 – base plate, 6 – rolled pipe

In the process, a pipe is put in rotations, and its radial straining takes place through four rolls symmetrically arranged in relation to the deformed pipe (Fig. 2). The location of the rolls in relation to the pipe is determined by the conical surface of the *1* fixing sleeve connected with body *2* by a thread, so setting the sleeve in rotations causes its axial displacement, and simultaneously starts radial shifting of rolls *4*, and that motion makes it possible to receive a conical pipe. Conical pipe formation may occur with increasing or decreasing draft, and the pipe taper depends on process kinematics conditions, i.e. lengthwise displacement speed of forming rolls and their radial shifting speed.

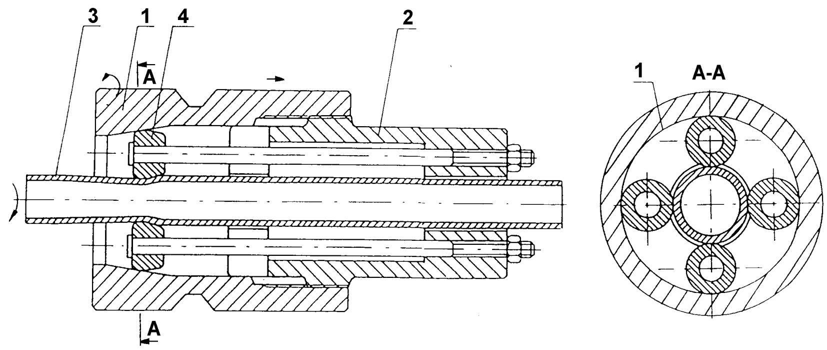

Fig. 2. Cross-section of the conical pipe envelope rolling device; 1 – fixing sleeve, 2 – body, 3 – pipe, 4 – roll, 5 – mandrel, → - designation of particular element motion during the process

Process characteristics and experimental

In the process of conical pipe envelope forming, an input cylindrical pipe put in rotations, is drawn between four rolls, symmetrically arranged in relation to the deformed pipe, and the roll generator is declined at some angle in relation to the deformed pipe, so a gradual decrease of the outer diameter takes place. During the process, a transition of a given point through the plastic strain valley is connected with multiple entering in a zone of direct roll impact, and the total strain is a sum of unit strains resulting from each roll impact on the deformed pipe. Pipe plastic strains that are expressed by diminishing the outer pipe diameter and by lengthwise and radial strains, take place as a result of direct forming roll impact and zones of non-contacted interaction on the boundary of zones between forming rolls, in which elastic state prevails, as well as zones of plastic state. The enveloped formed of tapered tubes involves drawing the cylindrical part of a starting tube set in the rotary motion between radially moving rolls, whose generating lines are inclined at a certain angle relative to the axis of the tube being formed [1, 2]. During the production process, working rolls move together with the entire device along the rotating tube, and owing to a decreasing distance between the rolls, a tapered tube is obtained. The length and taper angle of the tapered surface of tubes are dependent on the peripheral speed imparted to the tube and the speed of displacement of the device along the tube. The displacement of the formed tube in relation to the rolls occurs by the action of axial force applied to the already deformed part of the tube. A feature specific to envelope forming of tapered tubes is that the resultant deformation representing changes of the overall dimensions (e.g. diameter, wall thickness and tube length) is a result of summation of component deformations occurring during multiple partial deformation in the plastic deformation area. In this respect, the envelope rolling process is similar to the process of forging on lever swaging machines, where unit deformation is small, however, large resultant deformation is obtained as a result of summation of partial deformations, and the correct shape of the forged material after the process is assured. It is a common view that forging on lever swaging machines assures uniform deformation, and the forged product is characterized by high accuracy of shape. During forging on lever swaging machines, anvils perform active motion when exerting pressure and idle motion when returning. In the envelope rolling process, forming rolls rotate with uniform motion, and no idle phase of the process occurs. Under the radial action of rolls and longitudinal stresses associated with drawing stresses, the radial flow of a tube material occurs in the range of the direct action of rolls. The surfaces of contact of the deformed tube with a particular roll are characterized by a small width in relation to the length. On a certain segment adjacent to the arc of contact of the tube with the roll, a zone of contactless plastic forming occurs, and then these segments pass into a zone of the elastic state of the deformed tube. When tapered tubes are formed by the discussed method, a given material point enters the plastic forming

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zone multiple times, then exits this zone to remain for some time in the elastic state in the zone between the forming rolls, and then again enters the zone of contactless plastic deformation. The shape of the plastic deformation region is characterized by the overall dimensions of the plastic deformation region, i.e. the outer diameter of the stock tube, D_p; the outer diameter of the tube leaving the plastic deformation region; the plastic deformation region length; the angle of generating line inclination relative to the tube axis; the shape of the surface of contact of deformed tube with the roll; and the shape of the contactless deformation zones. Having in mind the necessity of assuring a stable deformation of the tube, the deformation zone should be covered by a large possible number of rolls, although instances are known where plastic deformation is concentrated within a small volume in relation to the volume of material being deformed, e.g. spinning which is performed using a single roll. On the other hand, however, small diameter rolls may create difficulties in assuring their proper hardness. With the above-mentioned aspects in mind, the number of rolls seem to be from three to five. A decision to use four rolls was made. The angle of the taper of the roll tapered surface was chosen based on the criterion saying that the taper angle should be within the angles for which the force during sink drawing of round tubes reaches the smallest values (in practice, most often 12÷16°) [3, 4]. A tapered surface inclination angle of 14° was taken. It seems that this angle may be either larger or smaller as well, because, in the range of optimum angles, the effect of tapered surface inclination angle on the value of longitudinal force is relatively small. Rolls, together with the device, move along the axis of the rotating tube. At the same time, their mutual distance gradually decreases, thus the pressure of rolls on metal increases. By the combination of this effect with the displacement of the entire device along the axis of the rotating tube, a tapered surface of the tube is obtained.

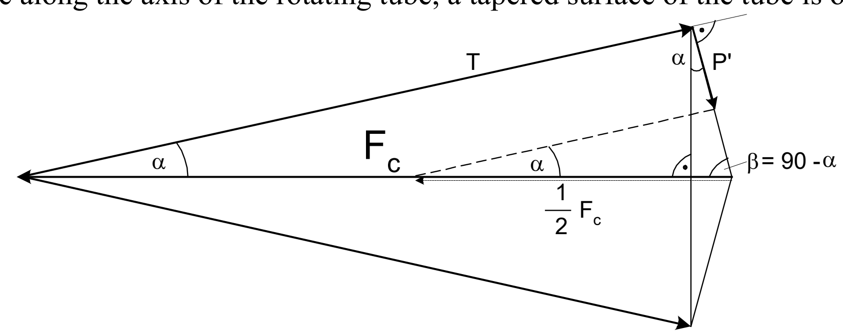

Fig. 3. Distribution of forces during the process of envelope rolling of conical pipes

In this process, a system of balance of forces acting in the rolling head on the tapered tube can be written for four rolls and a single longitudinal force, F_c, as measured extensometrically.

$$F_c = 4\,P'\sin\alpha \tag{1}$$

From the above balance system, the force of roll pressure on the tube, *P'*, has been determined:

$$P' = \frac{F_C}{4\sin\alpha} \tag{2}$$

In the process of envelope forming of tapered tubes, the displacement of a formed tube in relation to the rolls occurs by the action of axial force applied to the already deformed part of the tube. In addition to the longitudinal force, torque moment acts on the deformed tube segment resulting in tangential stresses, $\tau_{r\theta}$, which, together with the drawing stress, σ_l, cause some effort of the material. The reduced stress, according to the hypothesis of deformation energy, is equal to:

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$$\sigma_H = \sqrt{\sigma_I^2 + 3 \cdot \tau_{\theta r}^2} \tag{3}$$

and should be smaller than the yield stress for a given material condition.

Beyond the plastic deformation region, the material should be in the elastic state, and the coefficient of effort defined by the ratio of reduced stress expressed by Formula (3) to yield stress should be less that a unit, and practically should be in the range of *0.6÷0.9*. The smaller the coefficient of material effort, the higher the likelihood of a trouble-free completion of the process. The coefficient of material effort is defined by the following equation:

$$n = \frac{\sigma_H}{\sigma_p} \tag{4}$$

Example results obtained from the calculation of σ_H and n are given in Table 1. Figure 4 shows the relationship of the coefficient of material effort versus the tapered tube deformation.

Table 1. Summary of the results obtained from the calculation of material effort and stress intensity

No.	Tube outer diameter	Tube inner diameter	Tube deformation	Reduced stress	Coefficient of material effort	Yield stress
	D_z *[mm]*	D_w *[mm]*	$-\ln\frac{D_k}{D_p}$ *[-]*	σ_H *[MPa]*	n *[-]*	σ_p *[MPa]*
0	13.0	11.50	0.00	-	-	183.5
1	12.5	10.96	0.04	19.5	0.10	185.0
2	12.0	10.40	0.08	21.5	0.12	186.0
3	11.5	9.82	0.12	27.6	0.15	187.5
4	11.0	9.22	0.17	37.4	0.20	189.0
5	10.5	8.62	0.21	44.9	0.24	190.5
6	10.0	8.08	0.26	50.7	0.26	193.0

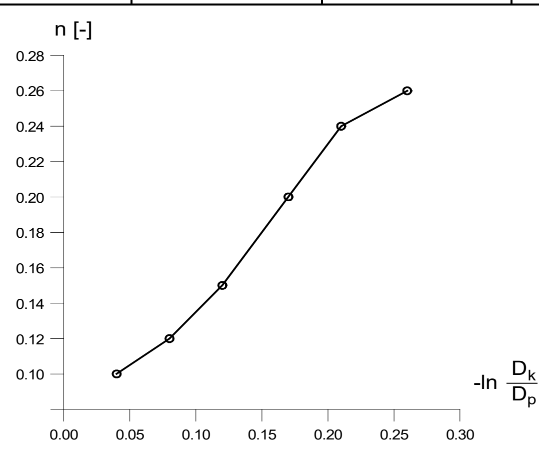

Fig. 4. Relationship of the coefficient of material effort vs. deformation

Another factor limiting the value of deformation in a single pass of a tube through the deformation head is the risk of losing stability during plastic forming.

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External friction occurring between the working surface of the tool and plastically deformed metal has a substantial effect on the course of plastic deformation, and thus on the service properties of the product (i.e. tapered tube) and the lifetime of the tools. Friction forces, i.e. the tangential components of the reactions of working roll surfaces on the surface of plastically formed tapered tube have substantial influence on the field and state of stresses in the deformed material, particularly in relation to working tool surfaces. The stress field has, in turn, an effect on the process of metal deformation, and thus on the movement of the metal surface in relation to the working tool surfaces, so also on friction forces. Thus, a certain kind of feedback occurs here. The performed microscopic measurements of tapered tube sections clearly indicate that the final wall thickness of the tube increases during the process, which means that the condition $\varepsilon_r = 0$, or generally $\sigma_r \neq \frac{\sigma_l + \sigma_\theta}{2}$, has not been satisfied, which depends on parameters affecting the value of stress state components. These parameters are the following: tool geometry, tube dimensions, friction coefficient, properties of rolled material, temperature, etc.

Summary

Envelope rolling of tapered tubes is used chiefly to reduce the outer tube diameter without a controlled change of the final tube wall thickness. The dependence of friction coefficient, μ, on the velocity of relative translational motion, W, of bodies in friction is complex and very difficult to establish, because the relative velocity of the displacement of a rolled metal in the rolling head is different at different points of contact of the tube with rolls, depending on the roll angle, α, rolled metal diameter, as well as on the magnitude of the reduction used. According to a suggestion contained in some works, including [5], it can be assumed that $\mu = f(W) = const.$ This assumption greatly simplifies theoretical considerations and at the same time does not lead to any significant discrepancies between theoretically obtained results and experimental test results. Assuming that the unit force, t, of the friction of metal with the roll has the μp value and its direction is coincident with the direction of the resultant velocity, V, then by changing the direction of the resultant velocity a change in the position of the vector of t friction force will be obtained. The position of the V vector of resultant velocity at a given point, and thus also the vector of t, is defined by the β angle.

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