Conical Pipe Envelope Formation Process

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Abstract

Conical pipes belong to a group of economical profiles, which find broad application in various metal products. Until now the conical pipes are manufactured by following methods: rolling on two-high mill in impressions with varying depth on the rolls perimeter; forging in lever swaging machine, formation in combined process of drawing and rolling, and rolling on skew rolling mill. Manufacturing of conical pipes belong to complicated engineering processes, and used until now methods do not allow to meet demand for conical pipes – 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 with till now known methods. It seems that the process of conical pipe envelope formation will allow to wide conical pipes assortment.

Keywords: Conical Pipe, Envelope Formation Process

Laboratory testing of conical pipes forming with an envelope rolling method – 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 take place through four rolls symmetrically arranged in relation to the deformed pipe (Fig. 2). Location of the rolls in relation to the pipe is determined by the conical surface of the fixing sleeve 1 connected with the body 2 by a thread, so when the sleeve is set in rotations, this causes its axial displacement, and simultaneously starts radial shifting of rolls 4, and through 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 the 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](image)

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**Process characteristics**

In the process of conical pipe envelope forming [5] 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 gradual decreasing of outer diameter takes place. During the process a transition of a given point through a 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 resulted from each roll impact on deformed pipe. Pipe plastic strains that are expressed by diminishing of outer pipe diameter, and by lengthwise and radial strains, take place as a result of direct forming rolls impact, as well as of zones of non-contacted interaction on a boundary of zones between forming rolls, in which elastic state prevail, and zones of plastic state.

**Conditions of tests conducting**

The tests were carried out on cooper pipes of a diameter Ø 13.5 x 0.75. The plasticity limit of the pipe material was: $s_p = 210$ MPa. Mean asymmetrical profile deviation from mean line - $Ra$, that characterizes an outer surface condition was $Ra=0.24$ µm, while the value for inner surface was $Ra=0.28$ µm.

Forming rolls (Fig. 3) were made of sintered carbides of the G20 grade, and their active faces were polished.

Fixing sleeve was made of quenched and tempered tool steel of NC10 grade.

The pipe rotational speed was 280 rpm, and the device body displacement speed was 0.130÷0.450 mm per 1 revolution.

The tests were carried out with use of the LT-4S bearing grease.
Course and results of tests

While beginning the process firstly the pipe was put in rotations, and then the fixing sleeve was rotated together with a mechanism of device body lengthwise displacement in relation to the deformed pipe. The process was conducted with rotating fixing sleeve, both in direction corresponding, as well as reversed, to the direction of deformed pipe rotations. The tests were carried out with roll lengthwise speed amounting within the bounds of 0.130 ÷ 0.450 mm per 1 revolution.

While process conducting the lengthwise force that acted on the deformed pipe was recorded through a strain gauges. To determine linear and non-dilatational strains in the plastic strain valley of the deformed pipe the process was stopped when assumed pipe outer diameter change was achieved, and then the linear and non-dilatational strains were determined. Carried out measurements of linear strains in circumferential, radial and lengthwise directions (Fig. 4) showed that decreasing of pipe outer diameter is accompanied increase of the pipe wall thickness with slight pipe elongation.

Fig. 4 Diagram of linear strain changes in circumferential, radial and lengthwise directions
Within the whole range of outer diameter decreasing the wall thickening grows monotonically as pipe diameter decreases, so in radial direction the strains are positive. Also strains in lengthwise direction are positive, but their value is much lesser than radial strains. On the other hand the strain in circumferential direction is negative, as the pipe perimeter decreases. From among three linear strains the circumferential strain is the highest one as far as absolute value is concerned, next the radial strain is slight lesser, and the lengthwise strain is the smallest one. The circumferential strains that express diameter change, and the radial strains expressed as wall thickness change are prevailing strains. At first approximation it can be assumed that the lengthwise strains are equal to zero, the pipe does not changes its length while it is formed, and the outer diameter decrease is accompanied by wall thickness increase. Such scheme of strains relates to stress state that rules in plastified zones.

Lengthwise stresses $s_l$, radial stresses $s_r$, and circumferential stresses $s_l$ act on a deformed pipe. Lengthwise stresses $s_l$ cause elongation of deformed material and its shortening in radial and circumferential directions. Radial stresses have similar effect, while circumferential stresses cause material twisting in circumferential direction, and dimension increase in radial direction, i.e. wall thickening. Conditions of stress equilibrium must be met between radial and circumferential stresses that act in a pipe (Fig. 5).

Projecting stresses that act on elementary volume in vertical direction it may be received

$$
\gamma \cos \varphi \sin \theta + \gamma \sin \varphi \cos \theta = 0
$$

When integrated and transformed it may be received

$$
\gamma \frac{g_0 \sin \theta}{r} = \frac{\sigma_0}{\sin \theta} \sin \gamma
$$

(1)

Fig. 5. Diagram of stress pattern on valley section.

When friction forces are taken into account the equilibrium condition assumes the form
The above mentioned relationships show dependencies between radial and circumferential stresses on the pipe surface. Radial stress $s_r$ on the inner surface is equal to zero, so it is proper to enter mean radial values against the wall thickness. Similarly as in a traditional process of pipe drawing [6] it was assumed that a pattern of radial stresses $s_r$ is linear, and in this connection the mean radial stress is equal to a half of the radial stress on the outer pipe surface.

\[
\frac{s_r}{r_r \sin \gamma} = \frac{1}{2} \frac{g_0 \sin \gamma}{r_r (1 - \cos 2\gamma)}
\]  

(2)

From the equation it may be seen that for a given value of the stress $s_\gamma$, the radial stresses $s_{rs}$ are the higher the higher is the wall thickness to pipe diameter ratio. So when thick-walled pipes forming the radial stresses are higher than in course of thin-walled pipes deforming. During conical pipes forming the circumferential and lengthwise stresses prevail. These stresses must meet a condition of plasticity. When using the condition of maximum tangential stresses we may write:

\[
\frac{e_r}{e_{ss}} = \frac{2G'(s_r \gamma)}{2G(s_r \gamma)}
\]  

(3)

Lengthwise stresses $s_l$ have a positive sign, while circumferential stresses $s_\gamma$ have a negative sign. So if $s_l$ is small, then $s_\gamma$ is close to a value of plastifying stresses and they decide the strain characteristic, and on the other hand when $s_l$ is high then $s_\gamma$ is small and stresses $s_l$ will decisively influence on the strain pattern. Radial stresses will influence somewhat, too, especially when circumferential stresses $s_\gamma$ are high.

To analyze wall thickness changes we will base on physical relations between strains and stresses. [1,3,4]

\[
\frac{\gamma}{\gamma} \frac{d^2 r}{dt^2} - \frac{\gamma}{\gamma} \frac{d^2 \gamma}{dt^2}
\]  

(4)

If we take into account

\[
\frac{d^2 r}{dt^2} - \frac{d^2 \gamma}{dt^2}
\]  

(6)

and then divide on both sides we will receive

\[
\frac{d^2 r}{dt^2} - \frac{d^2 \gamma}{dt^2}
\]  

(7)
and at the same time the strain $d\epsilon_r$, equal to $dg/g$ describes wall thickness changes in a given cross-section while the $d\epsilon_r$, equal to $dD_r/D_r$ describes a diameter change. Taking into account, in the equation (7), the relationship (1) between radial and circumferential stresses in which the expression $\sin?/\sin?'$ was designated as $A$, and the plasticity condition (3), and also entering a $W$ coefficient that characterizes the lengthwise stresses to plastifying strain ratio $W=s_f/s_p$, when transformed, it was received

$$
\frac{dg}{g} \frac{2A \frac{g}{D_r} (??W) ? 2W ??}{? \frac{dD_r}{D_r} ?? W ? A \frac{g}{D_r} (? ? W)} ? n
$$

(8)

The circumferential strain $dD_r/D_r$ has always negative sign since deformed pipe diameter decreases monotonically, while the radial strain, depending on process realization conditions may be positive, negative or equal to zero. Here the relative lengthwise stress is a parameter that decides a wall thickness change character. The $W$ coefficient is contained in limits: $0=W=1$. For relatively small values of $W$, the radial strains to circumferential strains ratio has negative sign what means that wall thickness increases. For some value of the $W$ coefficient a function that describes strains ratio achieves a value equal to zero what means that wall thickness changes. Such condition occur when the expression (8) numerator is equal to zero

$$
2A \frac{g}{D_r} (??W) ? 2W ?? ? 0
$$

(9)

hence

$$
W ? \frac{2A ? \frac{g}{D_r} ??}{2A ? \frac{g}{D_r} ? 2}
$$

(10)

This means that a value of the $W$ coefficient for which wall thickness does not changes, depends on wall thickness to rolls diameter ratio. For thin-walled pipes the coefficient value approaches a value equal to $\beta/2$, and when we assume that $\beta=1.1$ then the coefficient is equal to 0.55. For pipes with relatively high wall thickness to diameter ratio a value of the $W$ coefficient for which wall thickness does not changes – decreases, for example for $2g/D_r$ equal to 0.3 the $W$ coefficient is equal to 0.423. Therefore as wall thickness to roll diameter ratio increases the $W$ coefficient value, for which wall thickness does not change – decreases. And thus thickening range during plastic forming diminishes.

For high values of the $W$ coefficient that depends on wall thickness to roll diameter ratio, a function determining radial strain to circumferential strain ratio has positive sign what means that wall thickness decreases. So if forming take place with relatively small $W$ coefficient value then wall thickening will occur. On the other hand if the $W$ coefficient reaches high values then outer diameter decreasing will occur initially with increasing wall thickness, then for some pipe diameter decreasing it will achieve a maximum value, and then it will decrease. In conducted tests the $n$ coefficient had a negative sign and was changing in limits from $-0.480$ to $-0.280$, what means that pipe forming takes places with wall thickness increase, and at the same time its intensity decreases as strains increase. Carried out measurements of wall thickness revealed that in the tested range of outer diameter decreasing the wall thickness increasing took place. We failed to achieve high values of the $n$ coefficient since when 30 % decrease of outer diameter was reached then the pipe stability loss followed.
A value of limiting strain in the process of conical pipe envelope forming that amounts to approximately 30 %, should be recognized as a high one comparing to other pipe deforming processes, as rolling on reducing mills, where diameter decreasing while passing one rolls set (two-high stands, or three-high stands) is of 0.1 order. Higher strains are achieved during free pipe drawing where strain is of 0.2 order.

Thus the relatively high strain value achieved in the conical pipe envelope forming process makes essential positive characteristic of this new process of conical pipe forming.

Wall thickness change depends also on wall thickness to roll diameter ratio. Higher values of the ratio diminish thickening amount.

Conducted tests demonstrated that during the conical pipe envelope forming, apart from desired linear
strains, the deformed pipe undergoes unwanted non-dilatational strains in three basic surfaces (Fig. 6, 7).

Presence of the strains testifies to tangential stresses occurrence in surfaces that are concentric in relation to the outer surface, in pipe longitudinal section and cross-section. The strain in concentric cylindrical surfaces is connected with tangential stresses action during forced pipe rotating with external torque occurrence. Braking influence of forming rolls causes speed variation along pipe length, what gives as a result non-dilatational strain in a cylindrical surface. The pipe receives higher non-dilatational strains on its outer surface. Non-dilatational strain in a pipe cross-section is connected with decreasing influence of forming rolls on angle speed diversification along the pipe radius. In this case, again, strains on outer surface are higher than strains on inner surface. Similar regularities refer also to non-dilatational strains in the pipe longitudinal section.

To characterize non-dilatational share in strain state Blazynski [2] introduces strain uselessness coefficient defined as a ratio of strain intensity including non-dilatational strains to strain intensity without non-dilatational strains

\[
\frac{? \cdot \frac{?}{?}}{?}
\]

(11)

Fig. 8 shows value of the coefficient for various diameter deformation values. It is seen on the Fig. 8 that the coefficient is barely by several per cent higher than in case of ideal strain. It is an essential characteristic of the conical pipe envelope forming process that says that non-dilatational strains share in a strain tensor is relatively small. Thus plastic strain energy is used mainly for effective linear strain, while barely several per cent of total energy go for non-dilatational strain.

In experimental part of the work linear and non-dilatational strains were determined and lengthwise stresses acting in input plane of the pipe from an area of plastic strain were determined, too. Basing on equilibrium condition of stresses that act on elementary ring, separated from strain area, and on plasticity condition, circumferential and radial stresses were determined. The data allow to determine tangential stresses on the basis of physical connections between stresses and strains in plasticity state.

\[
\begin{align*}
?_{1r} & = 2G'(?_{1r} \cdot ?_{1r}) \\
?_{1r} & = 2G'(?_{1r} \cdot ?_{1r}) \\
?_{1r} & = 2G'(?_{1r} \cdot ?_{1r}) \\
\frac{?_{1r}}{2} & = 2G'(?_{1r} \cdot ?_{1r}) \\
\frac{?_{1r}}{2} & = 2G'(?_{1r} \cdot ?_{1r}) \\
?_{1r} & = 2G'(?_{1r} \cdot ?_{1r})
\end{align*}
\]  

(12)

When both sides of the equation that contain linear and circumferential strains speeds are divided the plasticity modulus \( G' \) and time differential \( dt \) are eliminated, and stress state components and one at the time differential of linear and non-dilatational strains remain in the equations.

The process of envelope forming is significantly characterized by a possibility to obtain relatively high total strains with relatively small elementary strains during one roll passage. Undergoing strains meet a monotony condition, and due to their very small value (0.00037), strain differentials may be substituted by unitary strains.
As a result of transformations we will receive

\[
\begin{align*}
\frac{?_r}{\gamma} & \div \frac{2?_r}{?_r} (\frac{?_r}{?} \div ?_r) \\
\frac{?_d}{?} & \div \frac{2?_d}{?} (\frac{?_d}{?} \div ?_d) \\
\frac{?_f}{?} & \div \frac{2?_f}{?} (\frac{?_f}{?} \div ?_f)
\end{align*}
\]  \hspace{1cm} (13)

Fig. 8 Changes of f coefficient for various diameters of conical pipe

The equations allow determining mean values of tangential stresses during pipe forming (Fig. 9). Conducted tests revealed that non-dilatational strains are relatively small comparing with plastifying stress values. Small value of the stresses is connected with small value of non-dilatational strains.
Conclusions

1. In the process of conical pipe envelope forming the tensile lengthwise stresses and circumferential and radial compressive stresses act on deformed material, and at the same time circumferential stresses prevail. The stress condition that prevails in the strain area causes diminishing of outer diameter, increase of wall thickness, and slight pipe elongation.

2. Apart from desired linear strains the pipe undergoes (unnecessary) non-dilatational strains. These strains are greater on the outer surface than on the inner one.

References