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Residual Stress in Welded Pipe

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Abstract—In recent years, increasing attention has focused on the residual-stress distribution in welded pipe, since residual stress is often responsible for the failure of welded pipe in industrial equipment. Residual stress σ_{res} appears in each step of welded-pipe manufacture, which relies on cold plastic shaping. Accordingly, experiments based on nondestructive methods are needed to establish the residual-stress distribution in the pipe blank. In the present work, the residual stress is measured at different points over the external circumference of small- and large-diameter pipe, by means of a DRP-RIKOR portable X-ray diffraction system.

Keywords: welded pipe, plastic shaping, flexure, springback, residual stress, X-ray diffraction analysis

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Current world demand for pipe is approaching 100 million t/yr. Welded pipe accounts for more than 60% of the total: large-diameter pipe (diameter 530 mm or more), moderate-diameter pipe (114–529 mm), and small-diameter pipe (<114 mm) [1, 2].

In the last 10–15 years, firms in Germany, Japan, Austria, and Italy have created electrowelding systems for the production of pipe (diameter up to 630 mm, wall thickness up to 22 mm) from metal of strength category up to X80 by means of high-frequency welding. Such pipe is used in the oil and gas industry [1, 2] and in certain branches of engineering [3].

The use of pipelines has been dynamically expanding: in 2005, the total pipeline length reached 2 million km; in oil pipelines, the figure is approaching 500000 km. More than 2 billion t of petroleum and petroleum products passes through this pipeline network each year. New construction projects for oil and gas projects are currently in development, including pipelines from Russia to Western Europe and China [1, 2, 4].

In practice, single-seam welded pipe (diameter 1220 and 1420 mm, wall thickness 7.0–48 mm) is primarily used for pipelines on land and on the sea bed. They are produced by shaping sheet blanks on presses by the UOE and JUOE (JCO) systems or by shaping in rollers [2], with subsequent welding and final adjustment (Fig. 1). In each operation during its manufacture, residual stress σ_{res} appears in the welded pipe, since cold plastic shaping is employed.

In recent years, increasing attention has focused on the residual-stress distribution in welded pipe, since residual stress is often responsible for the failure of welded pipe in industrial equipment [2, 4]. Therefore, for small-diameter pipe used in the power industry, for example, σ_{res} is regulated in each step of the manufacturing process by Technical Specifications TU 14-3R-1970–2001.

Analysis of the stress–strain state of the shaped sheet indicates that, after the load is removed, springback occurs. Correspondingly, compressive residual stress $-\sigma_\theta$ appears at the outer surface, while tensile stress $+\sigma_\theta$ appears at the inner surface (Fig. 2) [5, 6].

However, in the shaping of the pipe blank, the metal experiences elastoplastic deformation under the action of force, according to the analysis in [7]. In flexure, the outer layers undergo extension, while the inner layers undergo compression (Fig. 2).

Therefore, experiments based on nondestructive methods are needed to establish the residual-stress distribution in the pipe blank [8].

We know that shaping is accompanied by nonuniform stress distribution. The differential equilibrium equation of an element in the deformation zone (Fig. 2) takes the form [5]

$$\frac{d\sigma_r}{dr} = \frac{\sigma_\theta - \sigma_r}{r}, \quad (1)$$

while the plasticity equation may be written in the following form on the hypothesis of maximum tangential stress for a plane deformed state

$$\sigma_\rho - \sigma_\theta = \pm\sigma_s. \quad (2)$$

Here the plus sign corresponds to the tangential-extension zone and the minus sign to the compression zone.

By solution of Eqs. (1) and (2), with the boundary conditions $\sigma_r = 0$ when $r = a$ and $r = b$; $\sigma_z = 0.5(\sigma_r + \sigma_\theta)$. Tomlenov obtained formulas for the stress distri-

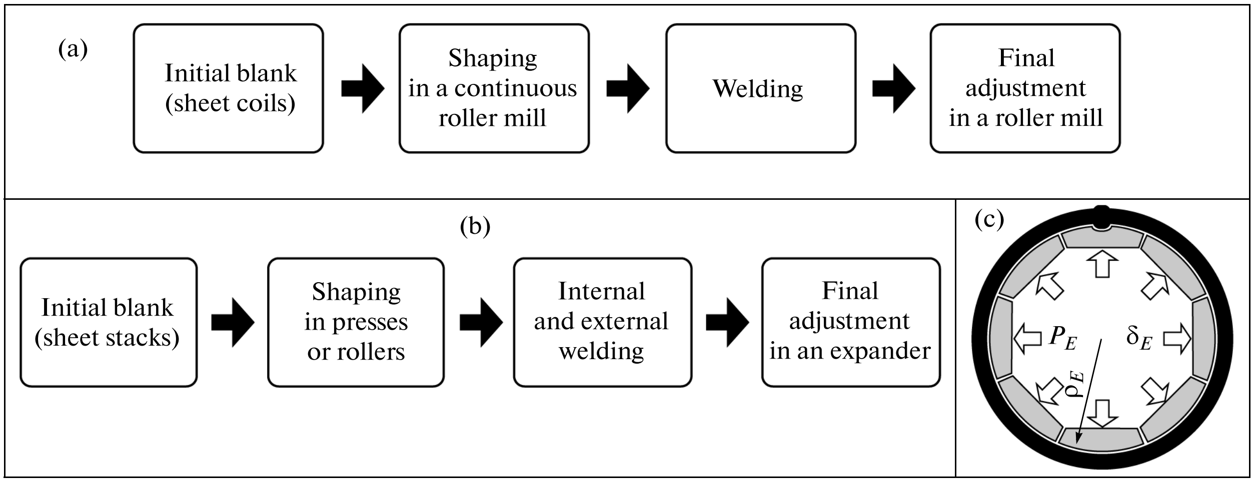

Fig. 1. Steps in the production of small- and moderate-diameter pipe (a) and large-diameter pipe (b) and shaping of large-diameter pipe in a mechanical expander (c).

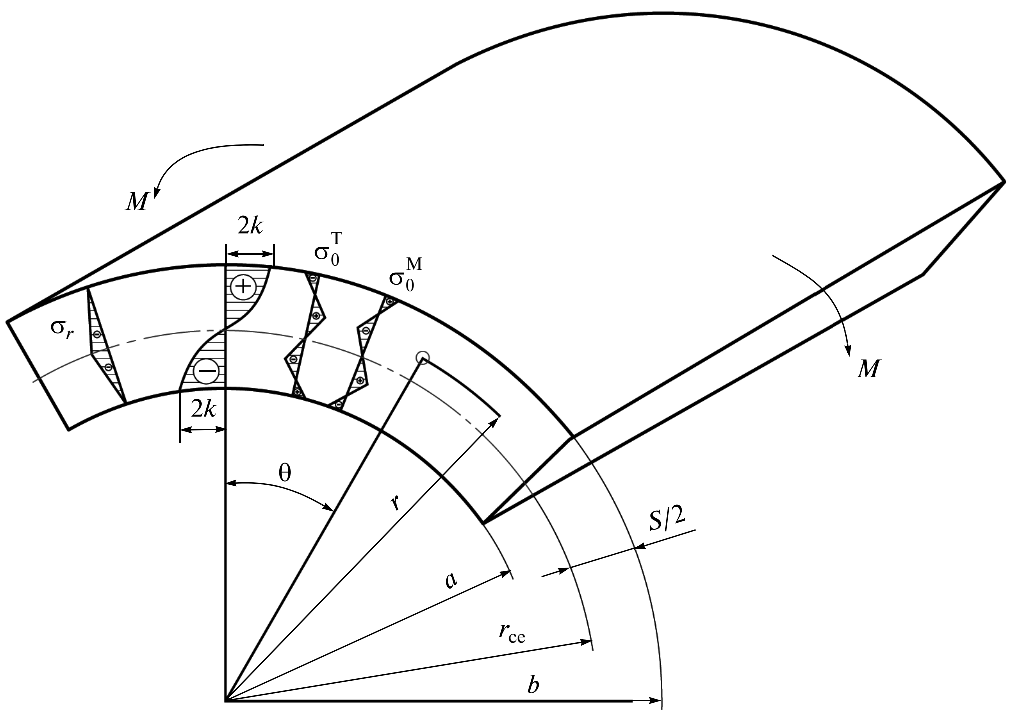

Fig. 2. Shaping of sheet and stress distribution over sheet thickness.

bution over the sheet thickness in pure flexure in [5] (Fig. 2)

for extension in the outer layer $\sigma_\theta - \sigma_r = 2k = \sigma_s$

$$\sigma_r = \sigma_s \ln\frac{r}{b} \quad \sigma_\theta = \sigma_s\left(1 + \ln\frac{r}{b}\right) \quad \sigma_z = \sigma_s\left(0.5 + \ln\frac{r}{b}\right),$$

for the compression zone $\sigma_\theta - \sigma_r = -2k = -\sigma_s$

$$\sigma_r = -\sigma_s \ln\frac{r}{a} \quad \sigma_\theta = -\sigma_s\left(1 + \ln\frac{r}{a}\right) \quad \sigma_z = -\sigma_s\left(0.5 + \ln\frac{r}{b}\right).$$

When the external load is removed, we observe springback of the sheet under the action of the residual stress shown in Fig. 2. Correspondingly, the tensile stress $+\sigma_\theta$ in the external layer is replaced by compressive stress $-\sigma_{res}^{T}$, according to the calculation for elastoplastic flexure of a beam in [5]. However, according to Matveev's 1965 graph of the actual residual stress in the sheet after load removal, tensile stress $+\sigma_{res}^{M}$ acts in the external layer (Fig. 3) [7].

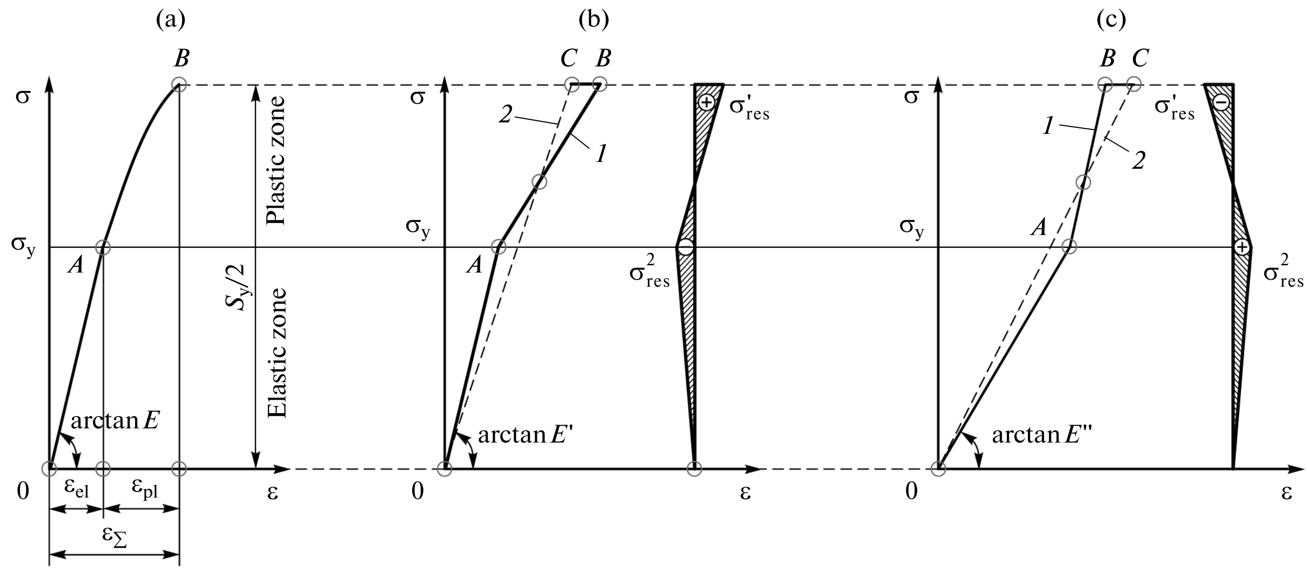

Fig. 3. Stress distribution in sample extension: (a) σ–ε measurements for real metal; (b) model proposed in [7]; (c) model proposed in [5]; (*1*) loading (*OAB*); (*2*) unloading (*OC*).

We now consider the extension of a standard sample and the σ–ε curve of the actual metal in the sheet, which is shaped by elastoplastic deformation at point *B* (Fig. 3). The strengthening σ_s of the blank with strain ε_{pl} at point *B* may be determined from a second-order curve [9]

$$\sigma_s = \frac{\sigma_B}{(1-\psi_n)^2}(1-2\psi_n+\psi). \quad (3)$$

The difference between the models of elastoplastic deformation proposed by Matveev and Tomlenov leads to different distribution of the residual stress over the thickness of the sheet, since in both cases the residual stress is determined as the difference between the tensile stress at point *B* and the compressive stress at point *C*. Hence, in the Matveev model, $\sigma_{res} = +\sigma_B - (-\sigma_C) > 0$, since $|\sigma_B| > |\sigma_C|$; in the Tomlenov model, by contrast, $\sigma_{res} = +\sigma_B - (-\sigma_C) < 0$, since $|\sigma_B| < |\sigma_C|$, as we see in Fig. 3.

The residual stress at different points over the external circumference of pipes may be measured by means of a DRP-RIKOR portable X-ray diffraction system [8].

In Fig. 4, we show the DRP-RIKOR portable system and the setup for measuring the residual stress in samples taken from pipe after welding, final adjustment, and heat treatment. The preparation of the experimental samples includes etching by an acid (50% HCl + 10% $FeCl_3$) and washing with weak baking soda solution.

Table 1 presents the residual stress measured at the surface of stainless-steel pipe ($D_p \times S_p = 40 \times 1.2$ mm) after welding by high-frequency current and after final adjustment, at the weld seam and some distance away. Table 2 presents the residual stress measured at the surface of 09Г2С steel pipe ($D_p \times S_p = 52 \times 2.5$ mm) after welding by high-frequency current and after final adjustment and heat treatment.

Table 1. Measured residual stress for pipe with $D_p \times S_p = 40 \times 1.2$ mm

Measurement point (distance from weld seam)	Residual stress, MPa	
	pipe after welding	pipe after final adjustment
Point 0 (at weld seam)	+145	+205
Point 1 (10 mm from weld seam)	+70	+145
Point 2 (90° rotation from weld seam)	+210	+130
Point 3 (180° rotation from weld seam)	–	+130

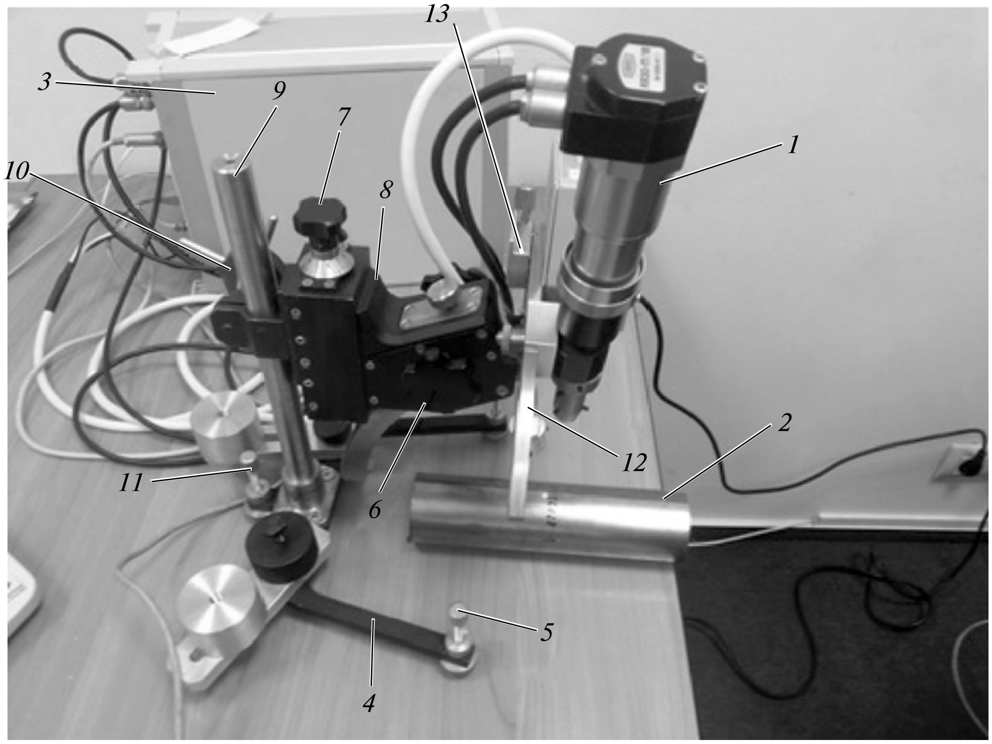

Fig. 4. DRP-RIKOR portable system and pipe template for measurement of the residual stress: (*1*) X-ray tube in housing; (*2*) sample; (*3*) power supply and electronic module; (*4*) base unit; (*5*) adjustment screw for base unit; (*6*) adjustment lever for support; (*7*) precise height regulator; (*8*) bracket; (*9*) mini column; (*10*) coarse height regulator (for vertical motion over the mini column); (*11*) adjustment screw for base unit; (*12*) support; (*13*) detector.

Analysis of the experimental data in Tables 1 and 2 indicates that, in small welded pipe, on shaping, welding, and final adjustment, tensile stress is observed at the outer surface, whereas only compressive stress is seen over the width of the initial cold-rolled sheet: σ_{res}^{sheet} = 120–150 MPa for stainless steel and σ_{res}^{sheet} = 30–60 MPa for 09Г2С steel.

Table 3 summarizes measurements by the same method for samples (fragments) from 10Г2ФБЮ steel large-diameter pipe (strength category K60) produced by various shaping technologies [8]. Note that pipe of diameter 1420 mm is manufactured by the JOE procedure and pipe of diameter 1020 mm by the UOE procedure [2]. However, all of the pipe undergoes final adjustment of the diameter on a mechanical expander. In the final adjustment of large-diameter pipe, the weld seam lies in the vertical plane so that it should not be subjected to deformation (Fig. 1c). Thus, the residual stress due to welding is retained in the weld seam, whereas the tensile stress $+\sigma_{res}$ in other parts of the pipe is partially converted to compressive stress $-\sigma_{res}$ as a result of expansion.

In the second stage, the axial and tangential residual stress in the middle and at the end of straight-seam

Table 2. Measured residual stress for pipe with $D_p \times S_p = 52 \times 2.5$ mm

Measurement point (distance from weld seam)	Residual stress, MPa	
	pipe after final adjustment	pipe after heat treatment
Point 1 (at weld seam)	+245	–30
Point 2 (5 mm from weld seam)	+140	+30
Point 3 (15 mm from weld seam)	+70	+35
Point 4 (20 mm from weld seam)	+55	+35
Point 5 (25 mm from weld seam)	+55	+30
Point 6 (30 mm from weld seam)	+90	+30
Point 7 (90° rotation from weld seam)	+75	+30

Table 3. Measured tangential residual stress for samples of 10Г2ФБЮ steel large-diameter pipe (strength category K60)

Pipe dimensions $D_p \times S_p = 1420 \times 12$ mm		Pipe dimensions $D_p \times S_p = 1020 \times 26$ mm	
distance from weld seam, mm	residual stress, MPa	distance from weld seam, mm	residual stress, MPa
Center of weld seam	+220	Center of weld seam	+150
Point 2 (24 mm from weld seam)	–40	Point 2	+45
Point 4 (37 mm from weld seam)	–70	Point 4	–90
Point 5 (50 mm from weld seam)	–70	Point 5	–100
Point 6 (79 mm from weld seam)	–75	–	–

Table 4. Distribution of residual stress in cross sections of straight-seam large-diameter pipe

Point of σ_{res} measurement	Residual stress in pipe cross section, MPa			
	at center of pipe		at end of pipe	
	axial	tangential	axial	tangential
Point 1 (at weld seam)	+12	–5	+50	–25
Point 2 (90° rotation from weld seam)	+80	+40	–20	–25
Point 3 (180° rotation from weld seam)	+5	–60	+14	–5

large-diameter pipe is experimentally determined (Table 4).

The results confirm the presence of tensile stress, which may result in the appearance of various defects capable of fatigue failure of the metal in subsequent pipeline operation [4]. In long-term pipeline operation, failure is possible even at stresses no larger than the maximum permissible value, as a result of all the loads at the pipe surface, including the welding stress and the residual stress due to pipe manufacture [4].

CONCLUSIONS

Our results confirm Matveev's conclusion that axial and tangential tensile stress is present at the surface of welded pipe, both at the weld seam and within the welded sheet. Analysis of the tensile stress is important in predicting the failure of large-diameter pipe in the operation of gas and oil pipelines and also in selecting the best small-diameter pipe for use in specific engineering applications.

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