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# Influence of thick-walled cylinders length on the residual stresses generated during the single-cycle mandrelling

**V F Skvortsov[1a], A O Boznak[1b], A B Kim[1c] and A Yu Arlyapov[1d]**

[1]Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk, 634050, Russia

E-mail: [a]TMRI@tpu.ru, [b]Aleksey@tpu.ru, [c]Bogowhich@tpu.ru, [d]Arlyapov@tpu.ru

**Abstract.** The paper presents methodology and results of experimental study by Sachs method the effect of length of mandrelled thick-walled cylinders made of steel grade 50 (0.5% C) with 5 mm diameter hole, outer diameter of 15 and 25 mm on residual stresses. Based on the review of studies, it was noted that this effect may be both due to uneven process of mandrelling along the cylinder length and due to zero axial residual stresses on its faces. It was found that the length of cylinders has the strongest influence on axial residual stresses. With allowances between 0.9 and 7.1% and length reduction from 40 to 10 mm, the largest absolute value of axial residual stresses decreases from 210 to 50 MPa. It was noted that when the outer diameter of cylinders is 15 mm their length significantly influence on both hoop and radial residual stresses. With the above-mentioned decrease in cylinders length, absolute values of hoop and radial residual stresses in the region adjacent to the hole, depending on the mandrelling allowance, increase (from –135 to –205 MPa and from –45 to 55 MPa respectively, when allowance is 7.1%), decrease (from –315 to –235 MPa and from –135 to –95 MPa respectively, when allowance is 0.9%) and remain almost unchanged (when allowance is 3.4%). Impact of length on these stresses is weak when the outer diameter of cylinders is 25 mm.

## 1. Introduction

Mandrelling is an effective method of processing holes in parts such as hollow cylinders [1, 2]. It is used for holes with diameters d=1...150 mm and relative depth $L/d \leq 100$.

Mandrelling is accompanied by generation of considerable residual stresses in hollow cylinders [1, 3, 4]. (Under these stresses hereinafter, as usual, we will understand their average values along the length of the cylinder.) Residual stresses are mainly determined by allowance and number of mandrelling cycles, mechanical properties of the cylinder material and wall thickness ratio, which is characterized by the ratio D/d (D – is outside diameter of the cylinder). When the wall thickness ratio $D/d \leq 3$, both compressive and tensile hoop residual stresses can be formed in the zone adjacent to the hole. Impact of hollow cylinder mandrelling configuration (tension or compression) on residual stresses is weak [5]. The absolute value of residual stresses in the mandrelled hollow cylinders can be close to the offset yield strength $\sigma_{0.2}$ of the part material. It was established that in order to generate favorable compressive hoop residual stresses in the hole surface layer that enhance performance characteristics of the cylinders, the last mandrelling cycle must be performed with small allowance (about 0.01d).

Residual stresses in the mandrelled thick-walled cylinders can be significantly influenced by length of the cylinders. With reduction of the length of cylinders, mandrelling process becomes less uniform, as the length of entrance and exit regions, in which axial metal flow predominates, accounts for higher share of the cylinder length. Thereby, we can expect all components of the residual stresses in the mandrelled cylinders to depend on the cylinders length. Furthermore, since the axial residual stresses always vanish on the faces of the cylinder, the absolute value of these residual stresses decreases as the length of the cylinder decreases. Hoop residual stresses slightly change too. In addition, as the review of the abovementioned studies showed, influence of the hollow cylinder length on the residual stress formed after mandrelling is not studied experimentally. This, to a certain extent, limits application of mandrelling for manufacture of hollow cylinders of different lengths.

The purpose of the study is to investigate the influence of thick-walled cylinders length on residual stresses generated in single-cycle mandrelling experimentally.

## 2. Experimental procedure

Experiments were performed on samples made of steel grade 50 (0.5% C content, $\sigma_{0.2}$≈470 MPa, HB 2170...2290 MPa) with hole diameter of d=5 mm. The outer diameter D of the samples was 15 mm (D/d=3) and 25 mm (D/d=5). The length L of the sample was equal to 10 and 40 mm. Holes in the samples were twist drilled on a lathe and then reamed with hand reamers. Mandrelling in compression scheme was performed on the universal testing machine UME-10TM using special equipment [2]. Single-point carbide mandrels (carbide grade VK8, 8% Co and 92% WC) with cones angle equal to 6° and width of the cylindrical margin equal to 3 mm were used for mandrelling. Relative allowances a/d were 0.9%, 3.4%, 7.1%. Oil fluid MR-7 was used as a lubricant. Mandrelling speed was equal to 0.008 m/s. After mandrelling, in order to ensure required accuracy, external surface and faces of the samples were subjected to fine grinding. Three samples were used in each experiment.

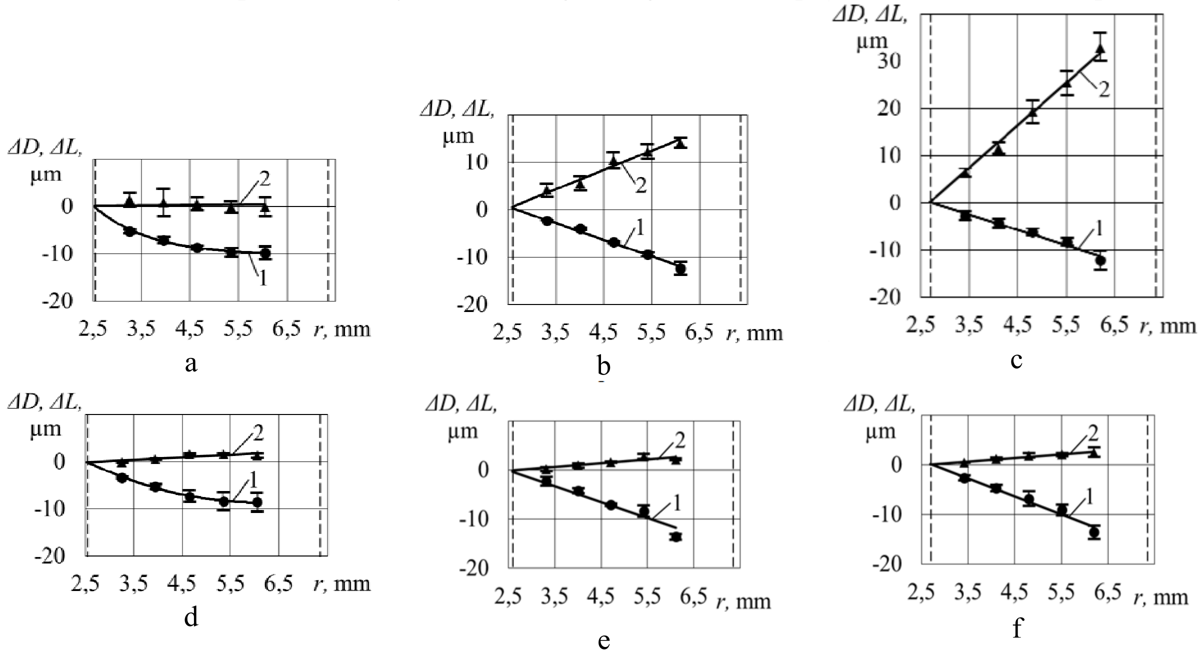


Figure 1. Dependence of change in outer diameter (1) and length (2) of the mandrelled samples with D=15 mm on the internal surface radius: *a* – a/d=0.9%, L=40 mm; *b* – a/d=3.4%, L=40 mm; *c* – a/d=7.1%, L=40 mm; *d* – a/d=0.9%, L=10 mm; *e* – a/d=3.4%, L=10 mm; *f* – a/d=7.1%, L=10 mm. Dotted lines show internal and external surfaces of the samples

Residual stresses were found by Sachs method using I.A. Birger's formulas [6]. In accordance with this method, 0.7 mm thick layers of metal were incrementally removed from the inner surface of the samples on a CNC wire-EDM machine model DK 7725 (PRC), resulted changes in external diameter and length were measured. External surface diameters were measured on an ultra-optimeter (Carl Zeiss Jena, Germany) with an accuracy of readings equal to 0.0002 mm. Length of the samples was measured with a mikrokator (accuracy of readings equal to 0.0005 mm) fixed in a stand. External diameters of 40 mm long samples were measured in three cross-sections located in the middle and at a distance of 2 mm from the sample faces. External diameters of 10 mm long samples were measured only in two cross-sections located at a distance of 2 mm from the sample faces. Diameter of the sample external surface was taken as the average of the measured values. Length of the sample was considered equal to the average of the two extreme values of the measured lengths.

Figure 1 shows an example of relationships between the change of outer diameter ΔD and length ΔL of the samples (D=15 mm) and the radius of the internal surface (95 per cent confidence intervals are given near the average values). These and other similar dependences (for samples with D=25 mm) were approximated using Statistica 8 with straight lines and second-degree polynomials, which equations were then used to calculate residual stresses. Young's modulus $E=2\cdot10^5$ MPa, Poisson's ratio $\mu=0.3$ were used. Calculations were performed using Microsoft Excel 2013.

### 3. Results and discussion

Distribution of hoop $\sigma_\theta$, radial $\sigma_r$ and axial $\sigma_z$ residual stresses along the radius r of the mandrelled samples (stress curves) are shown in figure 2 (D=15 mm), and figure 3 (D=25 mm). It can be seen that the hoop residual stresses are compressive in the zone adjacent to the hole and tensile in the zone adjacent to external surface in all the cases studied. Radial residual stresses on the hole surface and external surface are equal to zero, and are compressive in the rest of the part material. Distribution of axial residual stresses along the radius of the sample is more complex. For samples with D=15 mm and length L=40 mm, in the region adjacent to the hole, axial residual stresses are compressive when allowance is 0.9% (figure 2a), and tensile when allowance is 3.4% and 7.1% (figures 2b and 2c).

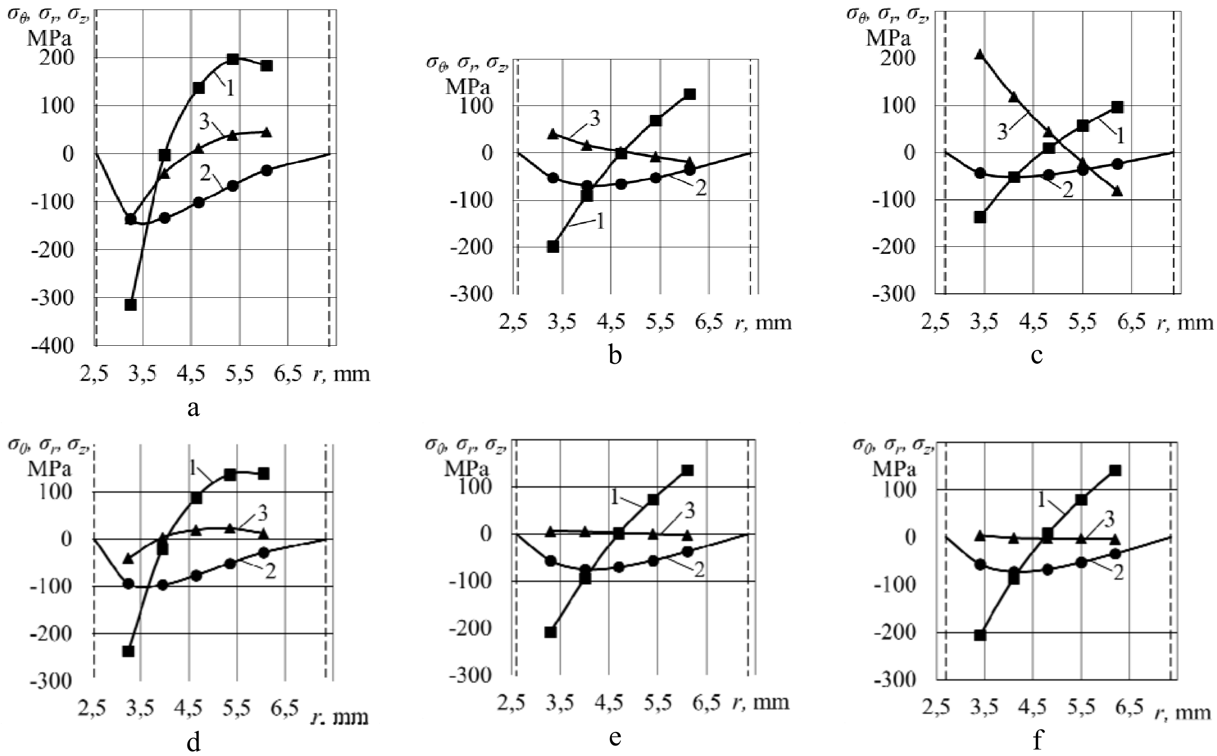


Figure 2. Curves for hoop (1), radial (2) and axial (3) residual stresses in the mandrelled samples with D=15 mm: a – a/d=0.9%, L=40 mm; b – a/d=3.4%, L=40 mm; c – a/d=7.1%, L=40 mm; d – a/d=0.9%, L=10 mm; e – a/d=3.4%, L=10 mm; f – a/d=7.1%, L=10 mm. Dotted lines show internal and external surfaces of the samples

For samples with D=25 mm, axial residual stresses are compressive in this region for all allowances used (figure 3). As can be seen from figures 2 and 3, axial residual stresses near the hole are balanced by axial residual stresses of opposite sign in the outer surface layer. The largest in absolute value stresses are the hoop residual stresses, which are close to the offset yield strength $\sigma_{0.2}$ of the cylinders material for samples with D=15 mm (figure 3).

Studies have shown that length of the samples has the strongest influence on the axial residual stresses. With the length reduction from 40 to 10 mm of the samples of both wall-thickness ratios, the largest absolute value of axial residual stresses decreases to the values smaller than 50 MPa (figures 2 and 3). Thus, for samples with D=15 mm, mandrelled with 0.9% allowance, these stresses near the hole vary from –135 MPa (figure 2a) to –40 MPa (figure 2d), and for samples mandrelled with 7.1% allowance – from 210 MPa (figure 2c) to values almost equal to zero (figure 2f). In samples with D=25 mm, subjected to mandrelling with 3.4 and 7.1% allowances, the axial residual stresses near the hole vary from –190 MPa (figure 3a) to –50 MPa (figure 3c) and from –75 MPa (figure 3b) to –10 MPa (figure 3d), respectively.

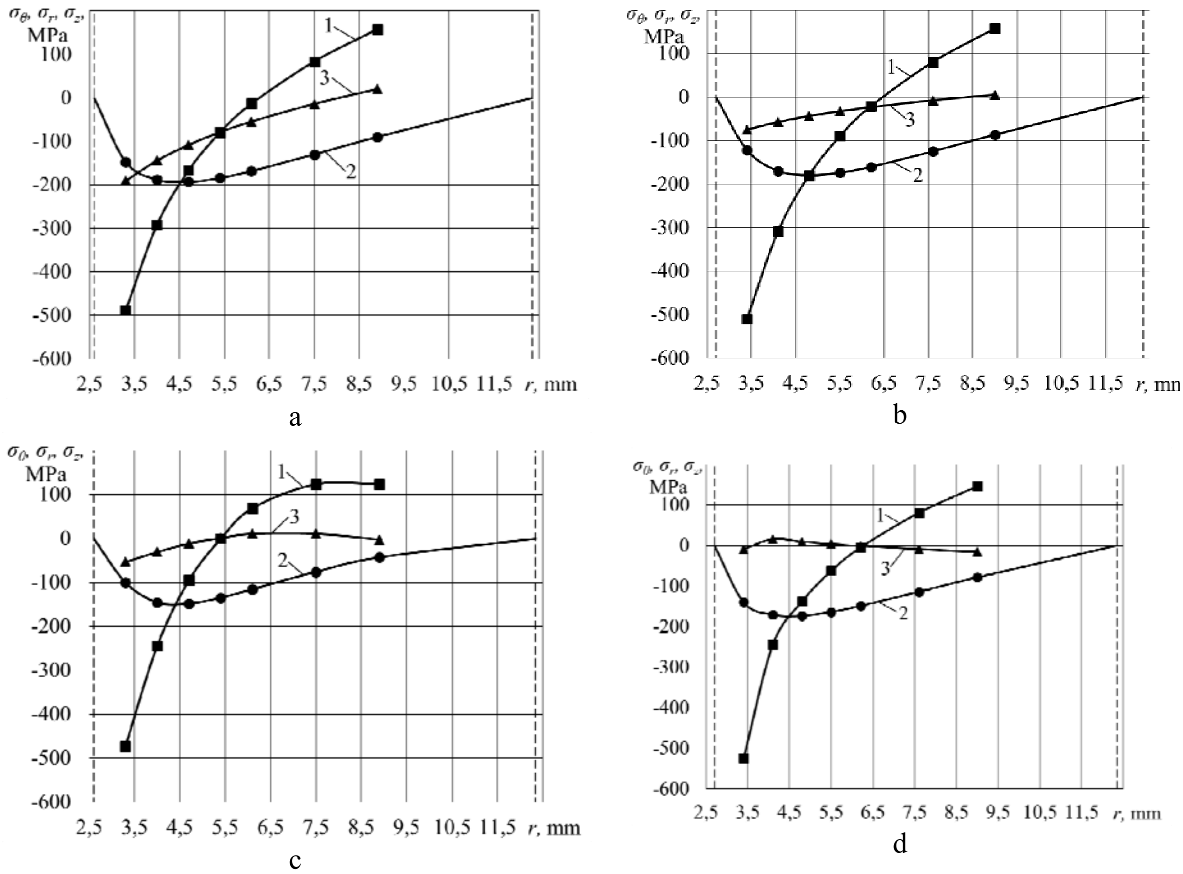


Figure 3. Curves for hoop (1), radial (2) and axial (3) residual stresses in the mandrelled samples with D=25 mm: a – a/d=3.4%, L=40 mm; b – a/d=7.1%, L=40 mm; c – a/d=3.4%, L=10 mm; d – a/d=7.1%, L=10 mm. Dotted lines show internal and external surfaces of the samples

When the outer diameter of samples D=15 mm, their length has a noticeable effect on both the hoop and radial residual stresses (figure 2). With the samples' length reduction from 40 to 10 mm, hoop and radial residual stresses may decrease, increase or remain almost unchanged depending on mandrelling allowances. Indeed, hoop and radial residual stresses near the hole reduce in magnitude from –315 MPa to –235 MPa and from –135 MPa to –95 MPa respectively when mandrelling allowance is 0.9% (figures 2a and 2d), these stresses remain almost unchanged when mandrelling allowance is 3.4% (figures 2b and 2e), increase in absolute values from –135 MPa, to –205 MPa and from –45 MPa to –55 MPa respectively when mandrelling allowance is 7.1% (figures 2c and 2f).

Impact of length on hoop and radial residual stresses is weak when the outer diameter of cylinders is 25 mm.

## 4. Conclusion

1. Length of mandrelled hollow cylinders has the strongest influence on axial residual stresses. With reduction of length of cylinders made of steel grade 50 (hole diameter is 5 mm, outer diameter is 15 mm and 25 mm, mandrelling allowances vary from 0.9 to 7.1%) from 40 to 10 mm, the largest absolute value of axial residual stresses decreases from 210 to 50 MPa.
2. If the outer diameter of cylinders is 15 mm their length significantly influences on both hoop and radial residual stresses. With the above-mentioned decrease in cylinders length, absolute values of hoop and radial residual stresses in the region adjacent to the hole, depending on the mandrelling allowance, increase (from –135 to –205 MPa and from –45 to 55 MPa respectively, when allowance is 7.1%), decrease (from –315 to –235 MPa and from –135 to –95 MPa respectively, when allowance is 0.9%) and remain almost unchanged (when allowance is 3.4%). Impact of length on these stresses is weak when the outer diameter of cylinders is 25 mm.

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