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ScienceDirect
Defence Technology 12 (2016) 473–479
www.elsevier.com/locate/dt

Reduction of the residual stresses in cold expanded thick-walled cylinders by plastic compression

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Received 27 April 2016; revised 8 August 2016; accepted 12 August 2016
Available online 1 September 2016

Abstract

We suppose that in order to maintain high accuracy of holes and to lower residual stresses after cold expansion of thick-walled cylinders, which undergo cross-section plastic deformation, it is necessary to perform axial plastic compression and subsequent cold expansion with small interferences. To test this hypothesis, we studied hoop, radial and axial residual stresses in cylinders made of carbon steel AISI 1050 with hole diameter of 5 mm, outer diameter of 15 mm and length of 30 mm by Sachs method as well as accuracy of expanded holes. It is found that double cold expansion with total interference equal to 5.1% generates hoop residual stresses with largest absolute value equal to 284 MPa and ensures high holes accuracy (IT7). After plastic compression with strain equal to 0.5 and 1% the mentioned stresses reduced to 120 and 75 MPa respectively, and accuracy of the holes reduced as well. Subsequent cold expansion with small interference equal to 0.9% helps to restore holes accuracy (IT7) gained by double cold expansion and ensure that absolute value of hoop residual stresses (177 MPa) is lower compared to double cold expansion.

Keywords: Thick-walled cylinders; Cold expansion; Plastic compression; Residual stresses

1. Introduction

Thick-walled cylinders (cylinders with an outer diameter D at least twice the size of the inner diameter d) constitute a large group of parts with precise small diameter holes ($d \le 10$ mm). These parts include, for example, micro hydraulic and pneumatic cylinders, various bushings, guides, tubes, rolling bearing rings, etc. Improvement of surface finish [1,2] and accuracy of small diameter holes [3–5] is an actual task and requires the development of new methods of processing and cold expansion is one of the most effective methods of finishing and hardening of holes in such parts [4,5]. Cold expansion is the process of pushing an oversized tapered pin or mandrel through the hole. Along with high productivity, cold expansion helps to increase accuracy up to IT6–IT8, improve surface roughness to Ra 0.1–0.3 μm, considerably work-harden surface layer and generate favorable compressive residual stresses [4–7]. Besides precise hole processing [4,5], cold expansion is used to raise fatigue strength of parts with fastener holes [8–12].

However, residual stresses generated during cold expansion of parts such as thick-walled cylinders can be undesirably high in some cases. If subsequent machining removes considerable allowances, workpiece undergoes substantial deformations and its accuracy decreases due to redistribution of residual stresses [7,13]. This is also possible due to relaxation of residual stresses during product operation [14]. In connection with the stated above it is of interest to investigate methods to reduce these stresses.

Vishnyakov [15] points out that one of the effective ways to influence value and distribution of residual stresses can be plastic stretching or compression with small (from 1 to 2%) strains. Yang et al. [16] performed finite element method simulation of quench residual stress reduction through cold stretching process and demonstrated effectiveness of the given method to reduce residual stresses. Koç et al. [13] showed that compression of Al 7050 blocks with strain from 1 to 4% reduced the residual stresses more than by 90%. Proskuryakov [4] suggested a method to reduce residual stresses in tubular samples after cold expansion. The method consists of pressing

Peer review under responsibility of China Ordnance Society.
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http://dx.doi.org/10.1016/j.dt.2016.08.002
2214-9147/

the samples onto a special mandrel with interference from 0.1 to 5% and subsequent plastic upsetting to axial strain in the range from 0.3 to 3.5%. The author also notes that this method can lead to decrease in accuracy of the sample hole.

Based on the review of studies [4,13,15,16], we can assume that one of the methods to manage residual stresses is axial plastic compression with low strains applied after cold expansion with high interferences and followed by cold expansion with small (approximately 1% of hole diameter) interference. It should be expected that residual stresses, generated after cold expansion with high interferences, have to drop during the compression [6,17]. However, a certain decrease in accuracy of a hole caused by cold expansion is inevitable. Subsequent cold expansion with small interference, when semi-elastic deformation takes place (the external surface of the cylinder remains in elastic state i.e. deformation of the external surface is smaller than 0.2%), helps to restore the accuracy. Additionally, as shown in Refs. [4,7], it helps to generate significantly lower residual stresses compared to cold expansion with high interferences, when cross-sectional deformation takes place (deformation of the external surface exceeds 0.2%).

The aim of this work is to experimentally investigate capabilities of plastic compression to reduce residual stresses in cold expanded thick-walled cylinders.

2. Experimental procedure

The experiments were aimed at determining residual stresses and carrying out accuracy analysis of holes subjected to double cold expansion, to double cold expansion followed by plastic compression with strain equal to 0.5 and 1%, and to cold expansion performed after plastic compression.

2.1. Test specimens

Experiments were carried out on samples made of carbon steel AISI 1050 with dimensions shown in Fig. 1. Samples were machined on a lathe DMG Mori CTX 310 ecoline, holes were drilled and reamed.

The total amount of samples was 25. They were divided into 5 lots. Samples from the first lot were cold expanded with high interferences. Samples from the second and the third lots were subjected to cold expansion with high interferences and plastic compression. Samples from the fourth and the fifth lots were subjected to cold expansion with high interferences, plastic compression and subsequent cold expansion with small interference.

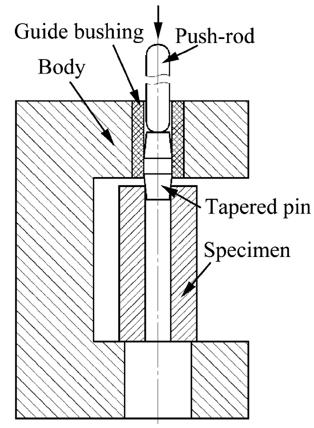

Fig. 2. Direct cold expansion.

2.2. Cold expansion

Direct cold expansion was used in this study (Fig. 2). To achieve the double cold expansion, two tapered pins were forced through the hole in the same direction. The total interference for the two passes was 5.1%. It was defined by the following equation

$$\textit{Total interference}\,\% = \frac{d_p - d}{d} \times 100$$

where d_p represents the diameter of the cylindrical part of the pin and d represents the specimen hole diameter. Subsequent cold expansion was performed with small interference equal to 0.9%.

The tapered pins used for cold expansion (Fig. 3) were made of WC-8%Co (92% of tungsten carbide and 8% of cobalt) by Mion Company (Tomsk, Russia) with dimensions shown in Fig. 4. Oil fluid MR-7 was used as a lubricant. Tests were performed on the universal testing machine IR5082-500. Cold expansion speed was equal to 0.008 m/s. Sample was held in the device shown in Fig. 2.

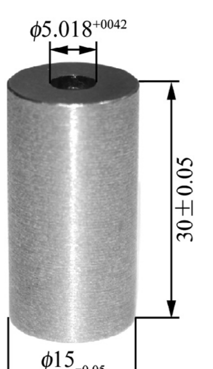

Fig. 1. Dimensions of the samples (mm).

Fig. 3. Tapered pins.

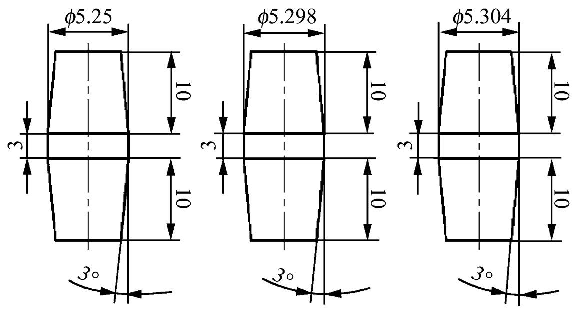

Fig. 4. Dimensions of the tapered pins (mm).

2.3. Plastic compression

Plastic compression with strain equal to 0.5 and 1% was performed on the universal testing machine IR5082-500. To ensure proper position of the samples during compression, their faces were preliminarily ground to remove any bulges left after cold expansion. Mixture of oil fluid MR-7 with molybdenum disulfide powder was applied to the faces of the samples to reduce friction. Sample was held in the device shown in Fig. 5.

2.4. Measurement of residual stresses

Residual stresses were found by Sachs method [18–20]. This method consists of independent successive removal of layers of metal from the inner or outer surface of the samples and measurement of resulted hoop and axial strains. We chose this method because it is a well-established technique to study distribution of residual stresses in cylindrical components that have rotational symmetry. This method has no limitations with regard to the depth of stress measurements and helps to measure the stresses throughout the entire thickness of the cylinder wall. Moreover, the method helps to define all three components of residual stress simultaneously. In addition, the given method is sufficiently accurate (nominal accuracy for steel is 45 MPa).

According to this method, 0.7 mm thick layers of metal were incrementally removed from the surface of the sample hole on a CNC wire-EDM machine model DK 7725; resulted changes in outer diameter and length were measured. External surface diameters were measured on the ultra-optimeter "Carl Zeiss Jena" (Fig. 6(a)) with an accuracy of readings equal to 0.0002 mm. The length of samples was measured using a Mikrokator 05IGP (Fig. 6(b)) with accuracy of readings equal to 0.0005 mm fixed in a stand. Outer diameter of the samples was measured in two longitudinal sections and in three cross-sections (in the middle and at a distance of 2 mm from the sample faces, as shown in Fig. 7(a)). Diameter of the sample external surface was taken as the average of the measured values. Length of the sample was measured as shown in Fig. 7(b), and was considered equal to the average of the two extreme values of the measured lengths.

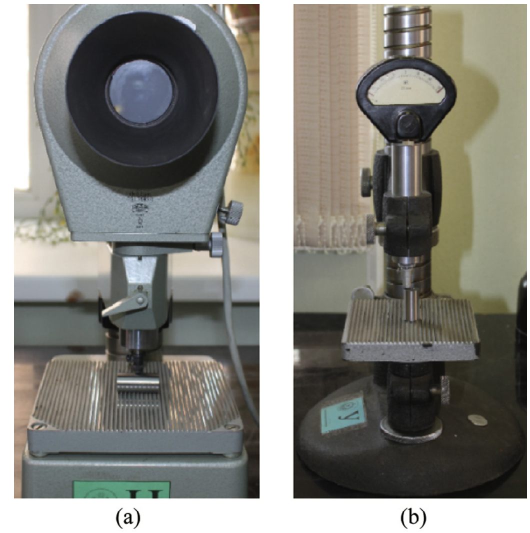

Fig. 6. Measuring devices:(a) ultra-optimeter;(b) Mikrokator.

External surface and faces of the samples were fine ground after plastic compression. This technique was used to ensure high accuracy of measurements of a sample length and diameter after boring. Since cold expansion leads to form distortion of the cylinder external surface and formation of bulges of metal displaced from the hole, it is impossible to perform accurate measurements without additional machining. Apparently,

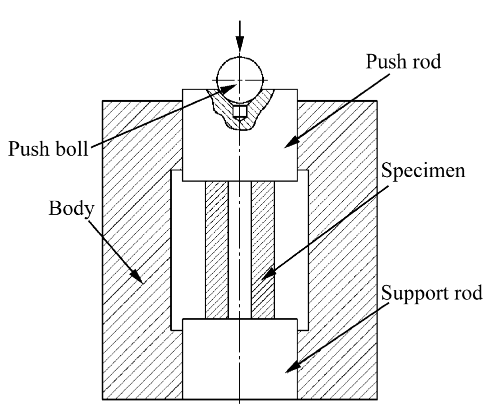

Fig. 5. Plastic compression.

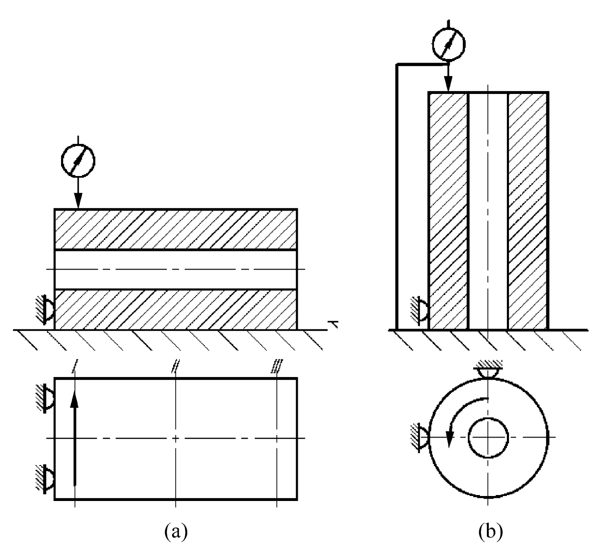

Fig. 7. Scheme of measurement:(a) outer diameter of the sample; (b) height.

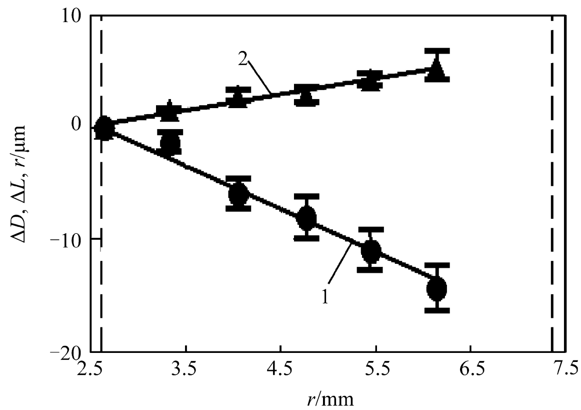

Fig. 8. Dependence of change of outer diameter 1 and length 2 of the cold expanded with high interference samples on the internal surface radius. Here and below, dotted lines show internal and external surfaces of the samples.

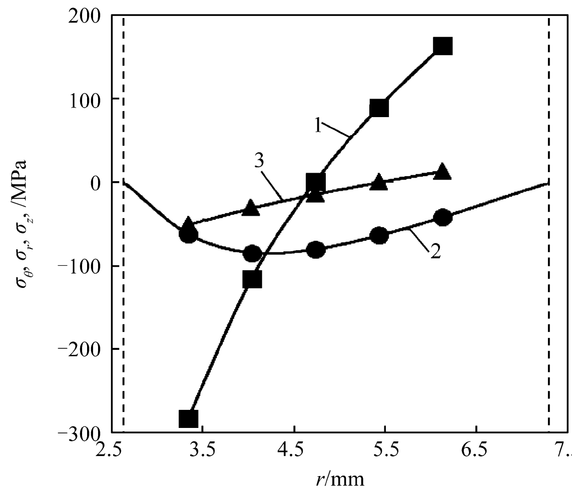

Fig. 9. Curves for hoop 1, radial 2 and axial 3 residual stresses in the samples double cold expanded with total interference equal to 5.1%.

fine grinding affects residual stresses generated after cold expansion, but considering the fact that cold expansion creates residual stresses in the entire volume of material and grinding (depth of cut is smaller than 0.01 mm) affects stresses only in surface layer, influence of grinding on the residual stress distribution can be considered negligible.

Fig. 8 shows an example of change of outer diameter ΔD and length ΔL of the samples during incremental boring, 95 per cent confidence intervals are also given. These results are intermediate outcomes and are used to calculate hoop and axial strain after cutting. Similar dependences were obtained in each experiment and then were approximated with straight lines and second-degree polynomials, in which equations were then used to calculate residual stresses.

Residual stresses were calculated using formulas proposed by I.A. Birger for the classic Sachs method [15]

$$\sigma_\theta(r)=\frac{E}{1-\mu^2}\cdot\left[\frac{R^2-r^2}{2r}\cdot\left(\frac{\mathrm{d}\varepsilon_\theta}{\mathrm{d}r}(r)+\mu\frac{\mathrm{d}\varepsilon_z}{\mathrm{d}r}(r)\right)-\frac{R^2+r^2}{2r^2}\cdot(\varepsilon_\theta(r)+\mu\varepsilon_z(r))\right] \tag{1}$$

$$\sigma_z(r)=\frac{E}{1-\mu^2}\cdot\left[\frac{R^2-r^2}{2r}\cdot\left(\frac{\mathrm{d}\varepsilon_z}{\mathrm{d}r}(r)+\mu\frac{\mathrm{d}\varepsilon_\theta}{\mathrm{d}r}(r)\right)-\varepsilon_z(r)-\mu\varepsilon_\theta(r)\right] \tag{2}$$

$$\sigma_r(r)=\frac{E}{1-\mu^2}\cdot\frac{R^2-r^2}{2r^2}\cdot[\varepsilon_\theta(r)+\mu\varepsilon_z(r)] \tag{3}$$

where R is the radius of the sample external surface, mm; r is the radius of the internal surface of the sample (cutting radius), mm; $\varepsilon_\theta(r)$ is the hoop strain on outer radius as a result of cutting internal surface to the radius r; $\varepsilon_z(r)$ is the axial strain on outer radius as a result of cutting internal surface to the radius r.

Young's modulus $E = 210$ GPa and Poisson's ratio $\nu = 0.3$ were used in calculations.

2.5. Assessment of hole accuracy

Sample hole diameter was measured with a dial bore gauge "Carl Zeiss Jena" with accuracy of readings equal to 0.002 mm. Measurements were performed in two longitudinal sections and in three cross-sections (in the middle and at a distance of 2 mm from the sample faces). Accuracy of holes was evaluated by the scatter of diameters as a difference between maximum and minimum diameters in the lot.

3. Results and discussion

Distribution of hoop σ_θ, radial σ_r and axial σ_z residual stresses along the radius r of the samples (stress curves) double cold expanded with a total interference equal to 5.1 % is shown in Fig. 9. This interference causes plastic–elastic hoop residual strain on the outer surface equal to 0.0047.

It can be seen that hoop and axial residual stresses are compressive in the zone adjacent to the hole and are balanced by corresponding tensile residual stresses in the external surface. Radial residual stresses on the hole surface and external surface are equal to zero, and are compressive in the rest of the part material. The largest in absolute value stresses are the hoop residual stresses, which are equal to −284 MPa near the hole surface. Dispersion of the sample hole diameters decreased from 0.042 mm to 0.009 mm (diameter after drilling followed by reaming was 5.018 + 0.042 mm, diameter after cold expansion was 5.254 + 0.009 mm).

Plastic compression of the samples performed after double cold expansion with total interference equal to 5.1% leads to a sharp decrease in hoop and radial residual stresses absolute value (Fig. 10). To a large degree, shape of the residual stresses curves remains unchanged. When the compression strain is 0.5% hoop residual stresses reduce in absolute value from −284 MPa (Fig. 9) to −120 MPa (Fig. 10(a)), and radial residual stresses from −85 MPa (Fig. 9) to −21 MPa (Fig. 10(a)). Increase in compression strain to 1% (Fig. 10(b)) leads to decrease in hoop residual stresses to −75 MPa, and decrease in radial residual stresses to −12 MPa.

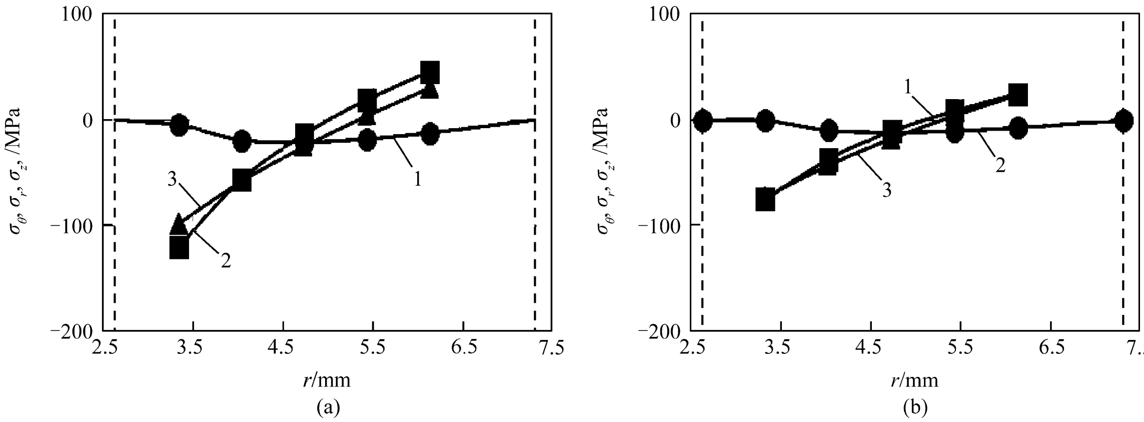

Fig. 10. Curves for hoop 1, radial 2 and axial 3 residual stresses in the samples after cold expansion with interference equal to 5.1% and plastic compression with strain 0.5% (a) and 1% (b).

The process of cold expansion generates deformations that are not uniform throughout the part and, as a result, leads to development of residual stresses. The reduction of residual stress level is achieved due to the fact that during plastic compression the uniaxial loading of a sample takes place, and after unloading elastic deformations will be uniform in magnitude and type.

At the same time, plastic compression leads to a distinct increase in axial residual stresses. The maximum value of these stresses after double cold expansion with a total interference equal to 5.1% is −51 MPa (Fig. 9), and after plastic compression with strains equal to 0.5 and 1%, increase to −99 MPa (Fig. 10(a)) and −73 MPa (Fig. 10(b)) respectively. This increase is probably due to non-uniform deformation of samples during compression caused by friction on the faces.

The same reason leads to decrease in accuracy of the sample hole diameter during compression. When compression strain is 0.5 and 1%, dispersion of the sample hole diameter increases from 0.009 mm to 0.012 mm and 0.015 mm respectively (hole diameter after compression with 0.5% strain is $5.254^{+0.012}$ mm, after compression with 1% strain is $5.251^{+0.015}$ mm).

Curves for residual stresses generated after subsequent cold expansion of plastically compressed samples with interference equal to 0.9% are shown in Fig. 11. This interference causes elastic hoop residual strain on the sample outer surface, which is equal to 0.00034. It can be seen that residual stresses are almost independent of the degree of plastic deformation during compression. The largest in absolute value hoop residual stresses is equal to −178 MPa, and is 38% smaller than hoop residual stresses in samples after double cold expansion with total interference equal to 5.1% (Fig. 9). Radial residual stresses increase to their initial values (−84 MPa), and axial residual stresses increase to −149 MPa. Dispersion of the sample hole diameters after subsequent cold expansion was 0.008 mm (hole diameter was $5.27^{+0.008}$ mm).

The experimental data (Table 1) show that plastic compression helps to reduce residual stresses in the thick-walled cylinders cold expanded with high interferences. We can suggest that

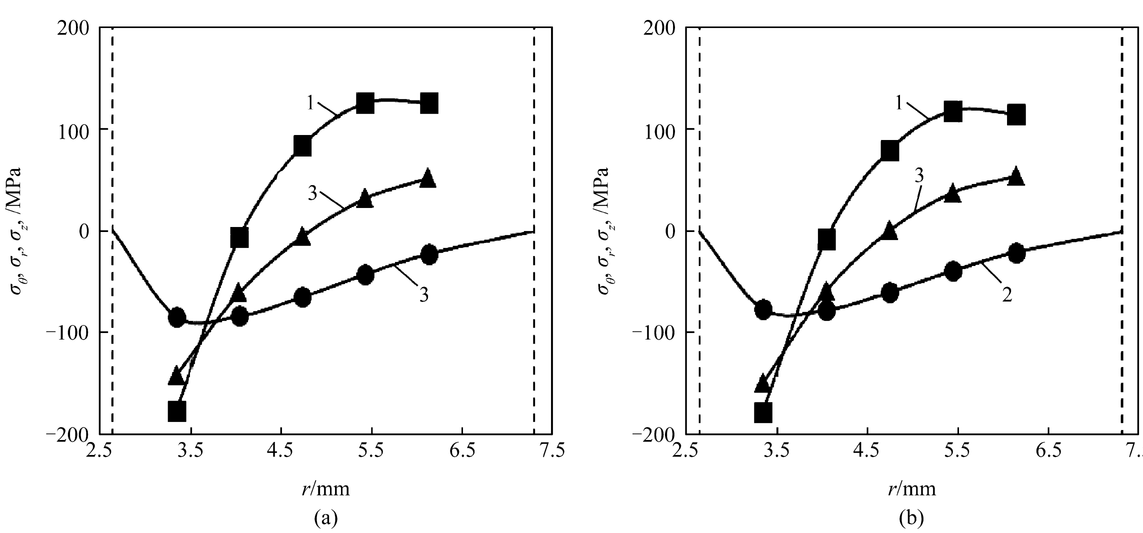

Fig. 11. Curves for hoop 1, radial 2 and axial 3 residual stresses in the samples after double cold expansion with total interference equal to 5.1%, plastic compression with strain 0.5% (a) and 1% (b) and subsequent cold expansion with interference equal to 0.9%.

Table 1
Summarized experimental data.

Process type	Residual stresses in the surface layer/MPa			Hole diameter dispersion/mm
	σ_θ	σ_r	σ_z	
Drilling followed by reaming	–	–	–	0.042
Double cold expansion with total interference 5.1%	−284	−85	−51	0.009
Double cold expansion with total interference 5.1% and plastic compression with 0.5% strain	−120	−21	−99	0.012
Double cold expansion with total interference 5.1% and plastic compression with 1% strain	−75	−12	−73	0.015
Double cold expansion with total interference 5.1%, plastic compression with 0.5% strain and subsequent cold expansion with interference 0.9%	−178	−84	−143	0.008
Double cold expansion with total interference 5.1%, plastic compression with 1% strain and subsequent cold expansion with interference 0.9%	−177	−77	−149	0.008

the most efficient method is to apply double cold expansion with high interferences along with axial compression with strain equal to 0.5%. This technique helps to reduce absolute value of hoop residual stresses by 58%, and decrease radial stresses by 75%. Dispersion of the sample hole diameters slightly increases (decrease of accuracy is smaller than one quality grade).

Further increase of deformation leads to a more substantial decrease in residual stresses along with decrease in hole accuracy. Subsequent cold expansion with small interference restores accuracy gained by double cold expansion and ensures lower hoop residual stresses, but makes manufacturing process more complex (requires additional operation).

4. Conclusions

The main results can be formulated as following:

1) Double cold expansion of holes in thick-walled cylinders made of carbon steel AISI 1050 (hole diameter is 5 mm, outer diameter is 15 mm, length is 30 mm) with total interference equal to 5.1% helps to limit dispersion of the hole diameter within 0.009 mm (IT7). Along with it, residual stresses are generated in the bulk of the cylinders. The largest in absolute value stresses near the hole surface are the hoop residual stresses, which are equal to −284 MPa, radial residual stresses are −85 MPa, and axial residual stresses are −51 MPa.
2) Plastic compression of the cylinders with 0.5% strain reduced absolute value of hoop residual stresses by 58% (to −120 MPa), and decreased radial stresses by 75% (to −21 MPa). Axial residual stresses increased to −99 MPa, and dispersion of hole diameters increased to 0.012 mm, what corresponds to IT7 (decrease of accuracy is smaller than one quality grade).
3) With increase in compression strain to 1%, hoop residual stresses decrease in absolute value by 74% (to −75 MPa), and radial stresses decrease by 86% (to −12 MPa). Axial residual stresses increase to −73 MPa, and dispersion of hole diameters increases to 0.015 mm, what corresponds to IT8 (decrease of accuracy is one quality grade).
4) After subsequent cold expansion of plastically compressed samples with interference equal to 0.9%, hoop residual stresses are equal to −178 MPa, and are 38% smaller than hoop residual stresses in samples after double cold expansion with total interference equal to 5.1%. Axial residual stresses increase to −143 MPa, and radial residual stresses increase to their initial values. Dispersion of the sample hole diameters decreases to 0.008 mm, what corresponds to IT7 (accuracy gained by double cold expansion is completely restored).
5) Based on the experimental data we can suggest that double cold expansion performed with high interference along with axial plastic compression with a strain smaller than 0.5% is the most reasonable. This helps to significantly reduce hoop and radial residual stresses, while the accuracy decrease is smaller than one quality grade.

We expect that this technique can be further developed by selection of a proper lubricant in order to reduce friction force on the faces of the cylinders during plastic compression. This may help to ensure more uniform deformation and as a result a smaller decrease in accuracy of holes. We plan to test the technique using finite element method and propose recommendations for optimum cold expansion parameters (interference, axial plastic strain during compression). It is also needed to assess feasibility of reducing residual stresses in cold expanded thick-walled cylinders by subsequent plastic stretching with small strains, and also combine cold expansion and plastic stretching into one process. This investigation is going to be carried out using not only real cold expansion process, but finite element method as well.

Acknowledgments

The authors gratefully acknowledge the guidance and role of the late Professor Vladimir Skvortsov during the conceptual stage of this study. The authors also wish to thank Lyudmila Petrova for invaluable metrological support. A.I.D. also thanks RFBR grant no. 15-08-01511a.

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