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The Analysis of Microhardness Variations of Hydroformed P265TR1 Steel Axisymmetric Elements from Tubes

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Abstract

The paper discusses the effect of upsetting ratio on distribution of the microhardness in longitudinal sections of hydroformed axisymmetric elements made from P265TR1 steel. The experimental research of hydroforming was carried out at a special stand which included a press with tooling and a hydraulic feeding system of oil. The measurements of microhardness were taken with a MATSUZAWA MMT-X3 Vickers hardness tester at a load of 100 g. The samples used in the tests were prepared from tube segments with a thin-wall ratio of 0.045. In the experiment, steel components were formed at upsetting coefficients of 0.07 and 0.09. For an established course of pressure and upsetting force, a series of steel components with exact representation of the die-cavity was formed. The paper provides a comparison of the microhardness distributions in three zones of longitudinal sections of axisymmetric elements at different degrees of material deformation. The greatest values of microhardness occurred in the area of cap for components at an upsetting coefficient 0.09.

Keywords: Mechanical properties, Hydroforming, Axisymmetric components, P265TR1 steel

1. Introduction

The hydroforming process was patented as a method of hydromechanical bulge forming of T-pipes [1]. It was used by the author of the patent for experimental investigations of equal and reducing T-pipes, X-shapes, Y-shapes and axisymmetric elements made from copper and different steel grades [2,3]. Since then, many research teams have been investigating this problem, especially for steel T-pipes and X-shapes. Some studies from recent years on this process concerning formation of axisymmetric elements have been reviewed [4-9].

Levy et al. [4] conducted a series of investigations into the evaluation of flat sheet properties on yield strength in a tube intended for the hydroforming process. In their experimental tests, three grades of steel with different properties (2.11 AKDQ, 2.42 AKDQ and 2.22 HSLA) were used. The mechanical properties of samples used in the investigations were determined by static tensile testing. They carried out a hydraulic burst test to simulate a hydroforming process of axisymmetric elements. From their results analysis, Leavy et al. [4] highlighted that the forecasting of the yield strength in the pipe based on the mechanical properties of sheets is revealed to be fairly accurate for the assumed effective strain.

Xu Y. et al. [5] investigated the influence of variable parameters of the process, including lengths of pipe before deformation, hydroforming velocity and changes of force on hydroformability of axisymmetric elements with rectangular sections. In experimental tests of the hydroforming process with pulsating axial loading, tubes of 304 stainless steel were used.

From the results of their analysis, it is clear that the lower velocity of pulsating force causes an increase in the formability of pipes made from 304 stainless steel.

Saboori et al. [6] conducted computer simulations (FEM) of the tube hydroforming process. On the basis of tensile testing tests, they experimentally obtained flow curves (stress vs. strain) for different grades of steel (321, 304L), INCONEL alloy 718 and aluminium alloy 6061. Saboori et al. [6] demonstrated that the predicted expansion and burst pressure results obtained from computer modelling were very similar to the experimental values.

In their studies, Lei et al. [7] discussed the effect of microstructure on the failure mechanisms of materials in the hydroforming process. The materials for investigations were welded pipes made from aluminium alloy. In experimental tests, different type of microscopes (electron back-scattered diffraction, TEM and SEM) for analysis of grain size, textures and local micro-crack areas were used. On the basis of the results, they identified large grains with high-misorientation in relation to the closest grains in the welds zone as the preferred crack nucleation areas in pipes during the hydroforming process.

Ra et al. [8] discussed the current applications of the hydroforming process as a technology for producing wire-reinforced aluminium tubes. They applied the finite element method (FEM) for analysis of this process by using various combinations of wires. Ra et al. [8] carried out a number of experimental investigations into the hydroforming process without defects of materials, such as incomplete bulging, buckling of wire and pipe cracking.

Cui et al. [9] investigated the influence of selected mechanical properties on wrinkling behaviour of thin-walled pipes in the hydroforming process. Cui et al. [9] conducted computer modelling (FEM) and experimental investigations of this process for pipes made from aluminium alloy (5052) and stainless steel (304).

Although the hydroforming process has been used for years, its technology for various shapes of pipe connections, parameters (especially changes of liquid pressure and forces) and design of tooling hasn't been completely tested so far. Knowledge of the mechanical properties of hydroformed components can provide a lot of very important information about the operational properties of finished products, especially the identification of a strain hardening of the material after cold work is important. For thin-walled components, the microhardness test should be used to characterise the mechanical properties of the tube after hydroforming.

The paper presents the results on hydroforming of axisymmetric elements made from steel tubes with thin-wall ratio of s_0 / D = 0.045 (where s_0 denotes the wall thickness of the pipe and D represents the outer diameter of the pipe). The tests aimed to establish the effect of the upsetting ratio on distribution of the microhardness in longitudinal sections of hydroformed axisymmetric elements from P265TR1 steel tubes. In Refs. [2,10], the relative upsetting ratio (as relative displacement of the punch) during the hydroforming process was derived as $\Delta l / l_0$ (where Δl denotes displacement of the punch and l_0 denotes the length of pipe before deformations).

2. Methodology

Taking into consideration the wide application of axisymmetric elements made from P265TR1 steel in the industry (e.g. in the manufacturing of valve balls), research on hydroforming involved using seamless steel tubes with an outer diameter of D = 22 mm and a wall thickness of s_0 = 1 mm (thin-wall ratio s_0 / D = 0.045). It was important that this material had good formability in metal forming processes. The tube segments had a length before deformations of l_0 = 90 mm (length of pipe segment resulted from the dimensions of used die insert in tooling for hydroforming).

The mechanical properties of the samples used in the investigations were determined by static tensile testing on a LabTest0.5.SP1 machine, which was compatible with Class 0.5 metrological requirements. The results are presented in Table 1. The testing was performed in accordance with international standard recommendations [11]. The flow curve of a sample made from P265TR1 steel is presented in Figure 2.

Table 1.
Mechanical properties of samples used in the experiment

R_m, MPa	R_e, MPa	A, %	$A_{11.3}$, %	Z, %
419	297	44	32	44

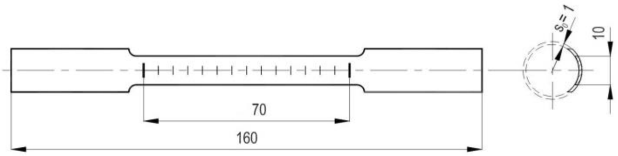

Fig. 1. Shape and dimensions of the samples used in the static tensile test

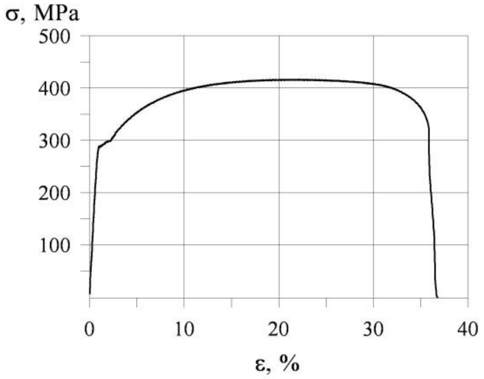

Fig. 2. Flow curve for P265TR1 steel

The experimental part of the investigations into the hydroforming process was performed at a testing machine (controlled by computer with Test&Motion software) equipped with a tooling (the main part of the tool is shown in Figure 3) and hydraulic feeding system [12]. The ZD 100 testing machine was modernised and calibrated. Its force measuring system was checked for Class 1 metrological requirements.

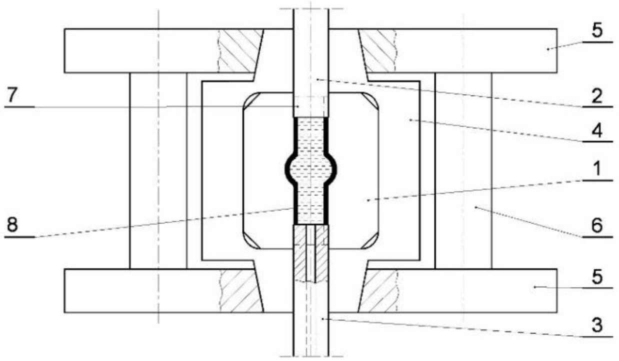

Fig. 3. Tooling for hydroforming used in experimental investigations, where: 1 - die insert, 2, 3 - upsetting punches, 4 - die housing, 5 - plates, 6 - leader pin, 7 - the sample before deformation, 8 - the sample after deformation [12]

The measurements of microhardness were taken with a MATSUZAWA MMT-X3 Vickers hardness tester at a load of 100 g, the measuring accuracy of which was compliant with ASTM E-384.

3. Results and analysis

The samples were hydroformed for the specified range of liquid pressures (Figure 4) at displacements of punch Δl = 6 mm and Δl = 8 mm (which corresponded to upsetting factors: $\Delta l / l_0 = 0.07$; and $\Delta l / l_0 = 0.09$).

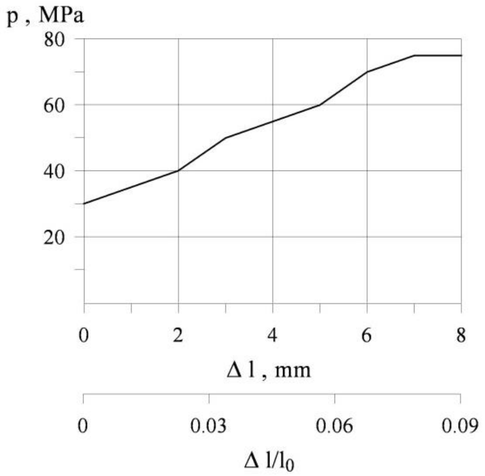

Fig. 4. Change in pressure obtained experimentally for hydroformed samples from P265TR1 steel pipes

The graph in Figure 5 shows the change in axial force vs. displacement of punch and the relative upsetting ratio obtained in the investigation of the hydroforming process.

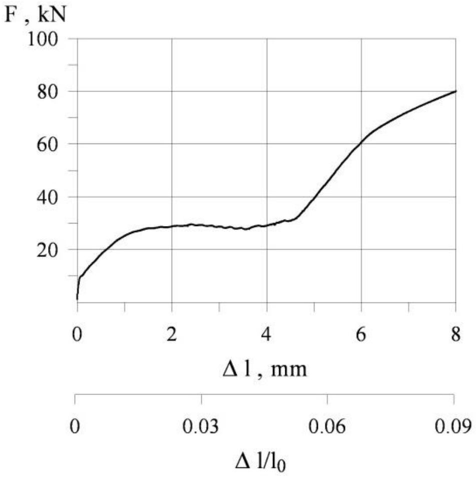

Fig. 5. Force waveform obtained experimentally for hydroformed samples from P265TR1 steel pipes

The experimentally obtained pressure and force waveforms began at established values (30MPa and 10 kN, respectively), which allowed for initial upsetting of samples. It was obligatory to seal the pipe segment by making indentations in the material using conical parts of the upper and lower punches.

As can be seen from Figs 4 and 5, an increase in the upsetting ratio caused an increase in the liquid pressure and axial force. The greatest values of axial loading obtained for upsetting coefficients 0.07 and 0.09 were 60.74 kN and 80 kN, respectively (a difference of 32%).

By applying appropriate pressure patters and changes of force (as can be seen in Figure 4 and Figure 5), it was possible to obtain axisymmetric element with exactly the same dimensions (d_1 = 30 mm, $h / d_1 = 0.67$ and $d_1 / d = 1.36$) as that of the die-cavity. The shape and geometrical parameters of hydroformed axisymmetric components are shown in Figure 6.

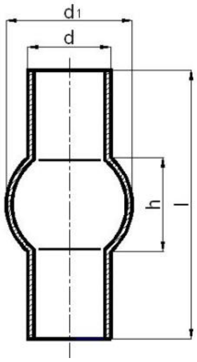

Fig. 6. Shape and geometrical parameters of hydroformed axisymmetric element

Examples of hydroformed specimens from steel tubes with a thin-wall factor of 0.045 and upsetting coefficients of 0.07 and 0.09 are presented in Figure 7.

Fig. 7. Examples of the hydroformed specimens obtained experimentally

Figure 8 presents the spacing of three measurement zones for microhardness measurements.

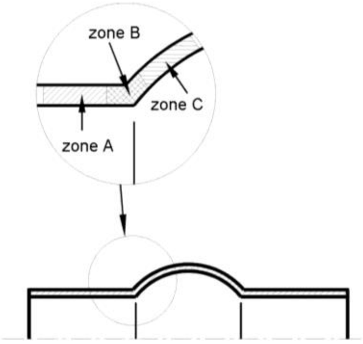

Fig. 8. Spacing of measurement zones for microhardness measurements in longitudinal sections of hydroformed specimens from steel tubes [13]

Figure 9 shows exemplary indentations in longitudinal sections of specimens after a Vickers hardness test.

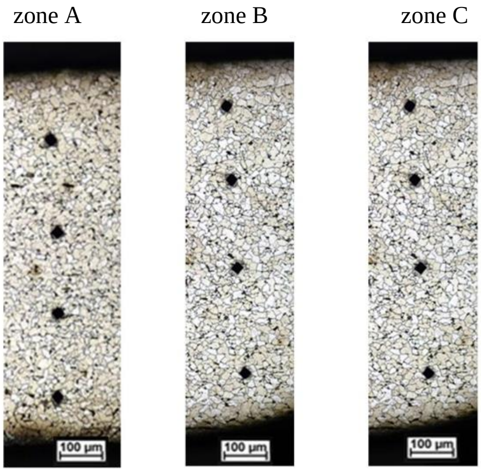

Fig. 9. Exemplary indentations for microhardness measurements in three zones of longitudinal sections of hydroformed samples

Each specimen was measured in three zones, the measurements were repeated three times, and the arithmetic mean was computed. The microhardness measurements did not demonstrate relevant differences. The results obtained on the basis of arithmetic values of measurements in different zones of longitudinal sections of hydroformed samples at upsetting factors of 0.07 and 0.09 are presented in Figure 10 in the form of points.

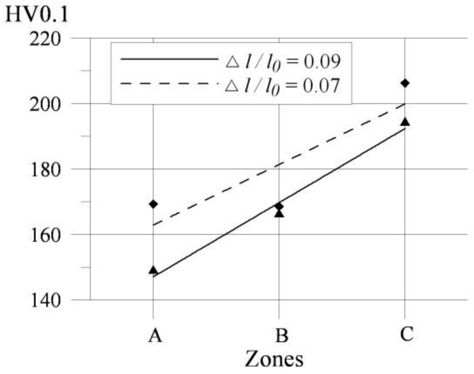

Fig. 10.Microhardness distributions in three zones of longitudinal sections of hydroformed samples at different upsetting ratios

The arithmetic mean of microhardness of specimens before deformation was 135.3 HV. Analysis of the results of the microhardness distributions (Figure 10) indicates an increase in the values of microhardness in the three zones of longitudinal sections of hydroformed components when compared with the microhardness of the material before deformation. A comparison of the microhardness in zones A, B and C indicates that despite the raised upsetting ratio, the nature of variations in microhardness of the samples is almost identical. The greatest values of microhardness occurred in zone C for specimens at upsetting ratios of 0.07 and 0.09. In this zone, microhardness raised with an increase in the upsetting ratio. The maximum value of microhardness for the hydroformed sample at Δl / l_0 = 0.09 amounted to 206.3 HV and was approx. 52% higher than the result for the pipe before deformation. Hydroforming components from tubes at upsetting ratios of 0.07 and 0.09 causes a thinning of the wall of the bulged part up to 10÷20% in relation to the wall thickness of the pipe before deformation. The greatest deformation and tensile stresses occur in this area (zone C of the component) [2]. The highest values of microhardness occurring in the spherical cup of specimens indicate a hardening of the material after cold work.

An evaluation of microhardness distributions was also made for zones A and B of the samples. Microhardness measured in section on the radius of body transition to the cap (zone B) of sample at Δl / l_0 = 0.07 did not differ substantially from the same area for the component with an upsetting coefficient of 0.09 (166.15 HV and 168.6 HV, respectively). In this zone, microhardness was approx. 22÷25% higher than the value for the material of pipe before deformation. The differences between the maximum values of microhardness measured in the cylindrical part of samples (zone A) and the values obtained on the radii of body transition to the spherical cap (zone B) didn't exceed 10%.

In the author's previous investigations [13] for hydroforming of copper samples at $\Delta l / l_0 = 0.05 \div 0.11$, the microhardness raised with an increase in the upsetting ratio only in the zone of caps of hydroformed samples. In other areas (cylindrical part of the element and zone of the radii of the body transition to the cap), no substantial differences were found [13].

4. Conclusions

On the basis of the described research, the following conclusions can be formulated:

1. An increase in the upsetting ratio caused an increase in the liquid pressure and axial force during the hydroforming process. The greatest value of axial loading was recorded in the hydroforming of samples with a higher upsetting coefficient of 0.09 (80 kN) than for specimens whose upsetting factor was 0.07 (a difference of 32%), which were bulged at a comparable pressure variation (the maximum values of liquid pressure did not exceed 70÷75 MPa).
2. A comparison of microhardness in three zones of the hydroformed elements indicated that despite increased coefficient Δl / l_0, the nature of variations in the microhardness of the samples is almost identical. In all investigated zones the microhardness was higher than the values for the tube before deformation. The maximum value of microhardness for an axisymmetric element at an upsetting ratio of $\Delta l / l_0 = 0.09$ amounted to 206.3 HV in the area of the spherical cap and was 52% higher than the result for the pipe before deformation.
3. The greatest increase in microhardness of the cap of hydroformed steel components was confirmed by the author's previous results obtained for copper components at the same relative ratios [13].

Established in paper parameters of hydroforming process (changes of liquid pressure and axial loading) can be applied in engineering practice to the making of valve balls (after cutting off the cylindrical parts of hydroformed elements). There is a need for further research on hydroforming of axisymmetric elements for other relative wall thickness s_0/D and relative ratios h/d_1 and d_1/d, especially in the range of a finite element analysis of effective strain and flow stress distribution in longitudinal sections of components after deformations to support the author's conclusions in the paper.

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