1. Introduction

The method of hydromechanical bulging of cross-joints was patented in 1973 [1]. Since then many research teams have been investigating the problem especially for steel T-pipes and cross-joints [2-8]. The technology involves placing a tube segment in a die-cavity, pouring some liquid over it and sealing the faces. As a result the liquid pressure rises and the pipe is upset. The basic parameters of the hydromechanical process of bulge forming are: liquid pressure and axial loading. The simulations of hydromechanical bulge forming were performed using MSC Marc software based on the finite element method. The calculation results were compared with the experimental data especially to study axial loading for different ratios \(d/D, s_o/D\) and for different variations of internal pressure. The results of numerical simulations of axial loading are in good agreement with the experimental data for established \(\mu = 0.15\).

As a result, we obtain bulged cross-joints with identical or different branch and outer diameters, the shape and dimensions being presented in Fig. 2.

Fig. 1. Bulge forming of a cross-joint

Fig. 2. Shapes and dimensions of cross-joints: 
 a) with \(d/D=1\); b) with \(d/D<1\).
Except for the liquid pressure, the upsetting force is also responsible for hydromechanical bulge forming. As the stub pipe bulge on two sides, the lengths can be considerable. By applying appropriate pressure, it is possible to obtain a cross-joint with exactly the same dimensions - radius and diameter - as those of the die-cavity.

The paper discusses the significance of the upsetting forces in the hydromechanical bulge forming of copper cross-joints with the same and different branch and outer diameters. The forces values obtained by computer modelling were compared with the experimental data. The analysis takes into account various $d/D$ and $s/D$ ratios and pressure changes.

2. Methodology

MacNeal-Schwendler software was used for modelling. The basic calculation package was the general-purpose MSC. Marc program [4-7]. As the analysis concerned plastic working, it was required to apply MES program as well. The model was developed and analysed with the aid of MSC/MENTAT presented in [6]. A simulation of the hydromechanical bulge forming process was conducted for copper cross-joints with a relative wall thickness $s/D = 0.05$.

Table 1 presents the dimensions and mechanical properties of the samples of copper pipe sections used both in the modelling and testing of the bulged pipes. The properties were determined experimentally by static tensile testing (columns 4-7) and using the Heyer method of stepped specimens (columns 8-9).

The calculations and the experiment aimed at the following final geometry: length of the tubular blank section after bulging $l = 70$ mm, diameters of the stub pipes $d = 20$ mm and $d = 22$ mm if all diameters are identical ($d/D = 1$) and $d = 18$ mm and $d = 16$ mm if the diameters are different ($d/D = 0.9$ and $d/D = 0.8$ respectively).

The pipe was covered with a square mesh consisting of 7800 coating type elements, the thickness of which was established to be 1 mm. It was assumed that the matrix and dies were stiff rigid and testing of the bulged pipes. The properties were determined with the aid of MSC/MENTAT presented in [6].

As the maximum values of the forces had to be assessed, the following tabulation was made (Table 2).

The greatest coincidence of the maximum values of upsetting forces obtained in the simulation and experiment was reported for the assumed coefficient of friction $\mu = 0.1$. The difference ranged 4.54–16.85%. The simulation results were almost always smaller than the experimental data. The only exception concerned the modelling of a cross-joint with $s/D = 0.05$ and $d/D = 1$, where the maximum force was 4.54% greater than that in the experiment. This was the case when the smallest difference between the force values was established for $\Delta l/l_0 = 0.42$.

4. Conclusions

1. The values of friction for the bulge forming process calculated by computer modelling were reported to

![Table 1](image)

| $D_0 \times s_0$ [mm] | $l$ [mm] | $s_0/D_0$ | $R_m$ [MPa] | $A$ [%] | $A11.3$ [%] | $Z$ [%] | $n$ | $C$ [MPa] |
|------------------------|-----------|-----------|-------------|--------|-------------|--------|-----|---------|
| $15 \times 1$          | 120       | 0.05      | 268         | 31.4   | 29.7        | 49.7   | 0.33 | 524     |
| $15 \times 1.5$        | 120       | 0.068     | 283.2       | 44.25  | 33          | 53.9   | 0.27 | 516.8   |
be highly dependent on the assumed values of the friction coefficient. The greatest agreement of the simulation and experimental data was reported for $\mu = 0.15$.

2. The value of the upsetting force in the bulge forming of cross-joints increases:

| Outer diameter of the tubular blank | Tube wall thickness $s_o$ [mm] | Tube wall thickness $s_o/d$ | Pipe branch diameter $d$ [mm] | Pipe branch diameter $d/D$ | Estimated pressure $p$ [MPa] | Established course of pressure | Maximum values of the axial loading for $\Delta l/l_0 = 0.42$ | Simulation [kN] | Experiment [kN] |
|-----------------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|-----------------------------|------------------------------------------------|----------------|----------------|
| 12                               | 3                            | 0.05                        | 4                           | 5                           | 6                            | 7                           | 8                                                             |         |         |
| 20                               | 1                            | 0.05                        | 20                          | 1                           | 20–50                        | 39.65 ($\mu = 0.1$)          | 46                                                            | 8         | 9         |
|                                  |                               |                             | 20                          | 1                           | 20–40                        | 37.97 ($\mu = 0.1$)          | 40                                                            | 1         | 2         |
|                                  |                               |                             | 18                          | 0.9                         | 20–50                        | 42.19 ($\mu = 0.1$)          | 48.6                                                          | 1         | 2         |
|                                  |                               |                             | 16                          | 0.8                         | 20–55                        | 46.69 ($\mu = 0.1$)          | 55                                                            | 1         | 2         |
| 22                               | 1.5                           | 0.068                       | 22                          | 1                           | 30–80                        | 60.7 ($\mu = 0.15$)          | 73                                                            | 1         | 2         |
|                                  |                               |                             | 20                          | 0.9                         | 40–80                        | 75 ($\mu = 0.15$)            | 81                                                            | 1         | 2         |

Fig. 3: Comparison of the force waveforms (a) obtained by simulation and experimentally for copper cross joints at $s_o/D = 0.05$ and $d/D = 1$, hydro-mechanically bulged due to pressure changes, b) at the assumed coefficient of friction $\mu = 0.1$ and $\mu = 0.15$.

Fig. 4 Comparison of the force waveforms obtained experimentally for a) copper cross joints at $s_o/D = 0.05$ and $d/D = 1$, $d/D = 0.9$, $d/D = 0.8$ hydro-mechanically bulged by means of pressure changes, b) at the assumed coefficient of friction $\mu = 0.1$.
• if there is a rise in the relative bulging ratio $\Delta l/l_o$, caused by an increase in the wall thickness in body area of the cross-joint [7] and in the material strength [4].

• if there is a decrease in the $d/D$ ratio caused for example by greater plastifying stresses [4] in body area near the faces.

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