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FORMING LIMITS OF THIN-WALLED PIPES

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ABSTRACT

This paper deals with the investigation of formability of thin-walled pipes in status of the biaxial state of stresses. The uniaxial tensile test for tube samples does not give a true picture of cases existing in complicated forming operations such as a lateral or biaxial bulging etc..
The biaxial tests more correspond to real states of stresses. In literature are described tools providing the process of bulging by fluid. These tools are more of less complicated.
This paper describes simple tool for biaxial tests applying the elastic tool as the forming medium. The first results and the theoretical way of main stress determination are mentioned too. The aim is to define the material characteristics of pipes and the values K and n.
***Key words**: Tensile test, radial expanding, thin-walled tube, polyurethane*

1. INTRODUCTION

Components made of thin walled tubes, profiles or tailored sheet plates are incorporated in light weight structures, the benefits of which are known not only in aircraft industry but are nowadays appreciated e.g. by car or another vehicles producers. Typical features of tubular components are high degree of complexity, buckling stability, strength and weight ratio. The prevailing manufacturing processes are forming, bending, bulging, axially symmetric stretching, flattening of the cross-section etc. Increasing demands on quality of components are obvious, defects as warping, cracks, thinning are unacceptable. They appear as a rule when a critical degree of deformation is exceeded. To predict mentioned defects and to ensure an appropriate component design, forming limit diagrams – FLD (e.g. Keeler-Goodwin's type) are determined and applied. The course and position of limit curves in FLD is very influenced by material properties, in fact by its plasticity. This iron material attribute can be defined by material flow stress curves, which are, in majority cases, determined by tensile or upsetting tests. Presented contribution points out, that basic tensile test, regarding to the formability problems, does not reflect with good conformity the stress and strain states prevailing in a critical section of formed tubular components.

2. PRELIMINARY INFORMATION ABOUT THE EVALUATION OF MECHANICAL PROPERTIES OF TUBES

In a tensile test the specimen is subjected to the uniaxial state of stress. This test enables to define the basic mechanical properties data as well as some indexes of plasticity (ductility, contraction, ratio $R_{p0,2}/R_m$, work hardening exponent n). The true stress and true strain dependence transformed in flow stress curves, e.g. by Hollomon's type stated below, is very frequent result.

$$\sigma_p = K.\varphi^n \qquad (1)$$

Concerning the sheet metal, the methodology of tensile test data evaluation is known. As far as the tubes are concerned, respecting the standards ČSN EN 10002-1 and ČSN 42 0322, three modes of tensile tests are used:

- Tubes with the diameter $D < 30$ mm are tested as a whole, clamping is performed by means of inserted shaped pins.
- When a tube diameter is $D > 30$ mm and wall thickness $t < 8$ mm, a longitudinal strip cut from the tube wall is recommended as a specimen. Stiffening clamping pins are needed.
- Tensile test of a specimen taken from the initial sheet metal (in case of welded tubes).

The above mentioned testing modes, reflecting the results of comparative experiments, were critically evaluated by [1] [2] [7] with the following conclusions:

- The results of tensile tests, due to the imparted uniaxial state of stresses, are not conforming with the state of stresses when bulging, expanding, etc. some sections of tubular components.. Here the biaxial state of stresses is prevailing
- Material characteristic K and n got by tensile tests of sheet metal specimen or cut-out strip can negatively influence the optimisation of forming processes factors or definition of forming limits parameters.

These problems were studied also by [3] [4] who proposed a testing fixture enabling biaxial stretching of tubular sample by means of a fluid. The methodology of this biaxial test was based on the bulging a set of samples with different pressure levels p. For each pressure level the geometry of the bulged profiles and thickness distribution along the meridian curve was measured. Using the theoretical approach, the material parameters K and n were obtained, finally verified and adjusted by FEM.

Reflecting the above mentioned results and recommendations the authors formulated following objectives:

- ➢ To evaluate the straining behaviour of thin walled tubes tested as a whole, applying conventional tensile tests.
- ➢ To carry out some bulging tests of tubes using an elastomer as the forming medium.
- ➢ To make full use of the existing forming fixture, having been previously used for fabrication of bulged tubular components by elastomer.

3. TENSILE TESTS OF TUBES

The material of tube specimens had to be the same in all planned experiments (tensile and bulging tests). With respect to the similarity with some components of jet engine, the tubular samples had the diameter D = 20mm, wall thickness t = 1mm, material ČSN 17248 (stainless steel), length l_o = 110 mm The relative wall thickness t/D = 0,05 ranks them into the group of very thin-walled [6] [8].

The samples were fixed in clamps of the tensile test machine according to the standards ČSN by means of inserted pins. Different tensile loads were applied, some of them up to the tube failure. In total, there were tested 8 samples made of CSN 17 248 stainless steel and 8 samples made of CSN 11 353 carbon steel with following results:

From the start of loading up to the failure a neck was generated along the whole length of all tubular samples. It means that all the straining process could be denoted as unstable on the contrary to the tensile tests of bars.

- There was analysed the meridian curve of the neck.
- After partition the samples in the longitudinal direction, the values of the thicknesses were measured in given points, as shown in Fig.1.

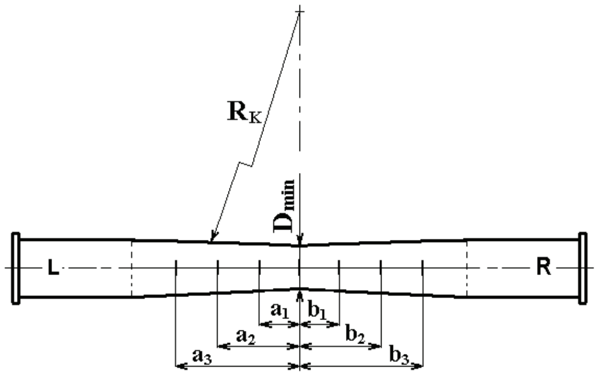

Figure 1 - Sketch of location of the measured points

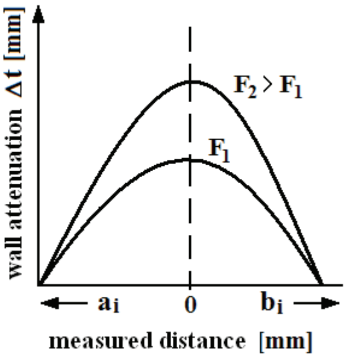

Figure 2 - Sketch of a wall attenuation for different loading force level

It can be stated, that the outline of the neck was generated uniformly and the changes of the wall thickness as well, represented by a smooth curves in diagrammatic plan – Fig.2.

Now, new sets of experiments are realised and by using straining grid the all phenomena of samples cross section changes would be analyzed in more details.

4. INNOVATION OF BIAXIAL TESTING PROCESS

4.1 Methodology of the test

The tooling which has been formerly applied for the manufacture of bulged tubular components was used (Fig.3). On the contrary to that common process (tubes were movable) here the ends of tubular samples were firmly clamped and bulged volume moved into the free space. Thus all the bulging deformation was performed against wall thinning. Samples were provided by circular straining grid. Polyurethane (hardness 95 ShA), as the elastic tool, was selected owing to its durability, possibility of high pressure application.

The loading expended on Polyurethane by the punch evoked radial expanding of the tube up to the bulge failure - a crack appearance.

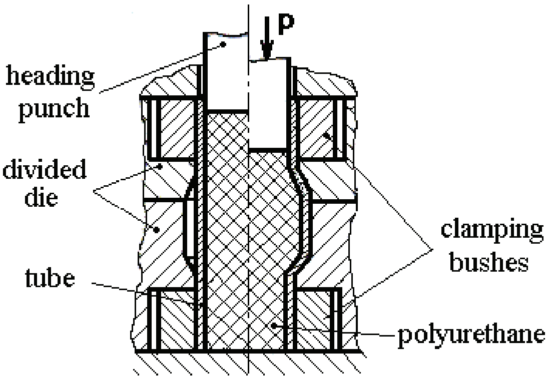

Figure 3 - Design of a test tool

Determination of data, necessaries for the application of the theoretical stress-strain analysis was based on measurement of bulged diameters in prescribed points (locations) as well as on the measurement of wall thicknesses in coincident locations (after axial cutting of the samples).

Data are related to average values across the different circular locations, the recorded upsetting forces, measured and calculated values of strains. Using volume constancy law, all together enabled to apply the analytical way of the flow stress parameters determination, as well as indexes of material plasticity etc. The results will be compared with those obtained by conducting uniaxial tensile tests of entire tubes and tensile tests of sheet metal samples.

The influence of Polyurethane friction on the generation and further development of bulged shape will be studied together with energy consumption of Polyurethane deformation process.

4.2 Procedure and results of biaxial tests

The diameters of bulged outline were measured along the meridian curve in 29 positions. The data obtained, using a PC program, were approximated by the circular curve, having the diameter R_2 (Fig.5). All detailed data are not listed, nevertheless it was proved acceptable coincidence between the approximated and measured arc. Differences existing near the transient section - bulged section and cylindrical part - were only (4÷7) %. Greater divergences occur at the upper section, here is a greater relative slip of Polyurethane and thus impeded friction could be the influencing factor.

As far as the definition of forming limits is concerned, a grid strain analysis near the crack is important. Results, listed in Tab.1, reflects the measurements of points 14 and 15 between which was detected D_{max}. The distance of the measured spot was 2,5 grid circle diameter from the crack. The average values of the final wall thickness are presented in Fig.6.

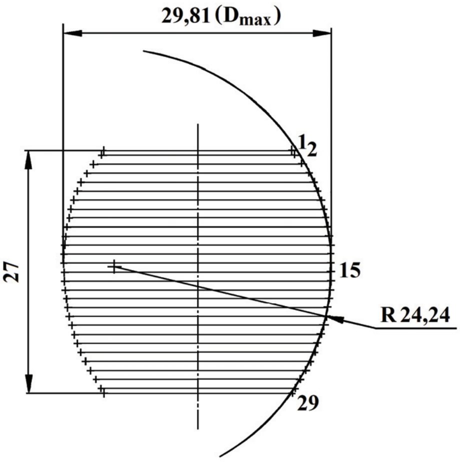

Figure 4 - Sketch of location of the measured points for stainless sample nr.4

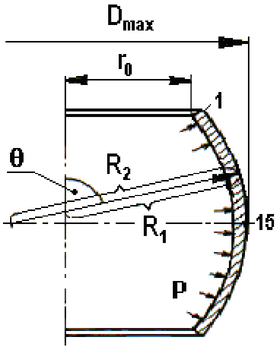

Figure 5 - Sketch of the geometrical values of a bulging part

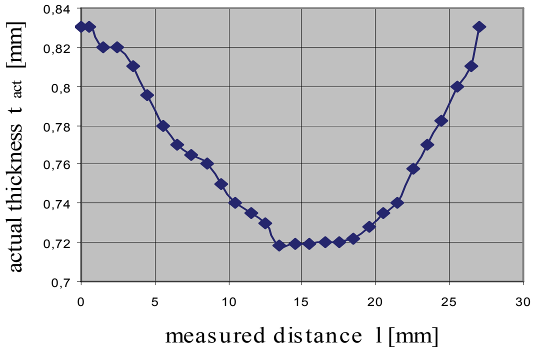

Figure 6 - Thickness of wall variance of a bulged section for stainless sample No.4

Tab.1 Calculated and measured values at the point of maximal bulging for sample No.4

Fixed ends of tube					
Point posit.	D_{max} [mm]	thickness [mm]	Main stress and σ_{ef} [MPa]	Strain indicator U_s	Strain indicator α
14	29.80	0.730	$\sigma_\theta = 1451.8$ $\sigma_m = 504.12$ $\sigma_{ef} = 1276.7$	0.88	0.347
15	29.81	0.718			

Thereinafter is illustrated a procedure which leads to the definition of material characteristics, reflecting a two dimensional stress situations and when geometrical parameters of the bulge are known.

Theoretical calculation of main stresses was accomplished by two equations. The equilibrium equation of axial outer and inner forces in section 15, where $R_1 = D_{max}/2$

$$2\pi R_1 t_{\min}\sigma_m = \pi\left(R_1^{\,2} - r_o^{\,2}\right)p \tag{2}$$

The equilibrium of inner and outer forces in section 15 described by Laplace's equation

$$\frac{\sigma_\theta}{R_1} + \frac{\sigma_m}{R_2} = \frac{p}{t} \tag{3}$$

The value of pressure p was determined by means of the coefficient k. This coefficient k reflects the uniformity of pressure distribution on internal surface of the pipe [5]. For fluid k =1, for polyurethane, being compressed in a closed space, it has less value. Coefficient k has the highest value (k ≅ 1). Being very high pressure was applied, the value of k = 0,85 was used in presented case.

Here, $p = k \cdot \frac{F}{S_p}$, where S_p is the area of the punch face.

There is a value of strain indicator by Kolmogorov noted in the table. For $\sigma_t = 0$ is

$$U_s = \frac{\sigma_\theta + \sigma_m}{\sqrt{3}\cdot\sigma_{ef}} \;, \tag{4}$$

where σ_θ is tangential stress, σ_m is meridial stress and σ_{ef} is effective stress. Also, there is strain indicator α which can be defined as:

$$\alpha = \frac{\sigma_m}{\sigma_\theta}\,. \tag{5}$$

The effective strain was determined by equation, which corresponds to biaxial state of stress

$$\sigma_{ef} = \sqrt{\sigma_\theta^{\,2} - \sigma_\theta\sigma_m + \sigma_m^{\,2}} = \sigma_\theta\sqrt{1-\alpha+\alpha^2} \tag{6}$$

5. DISCUSSION

When bulging is realised by fluid the pressure is uniformly distributed over the inner area of a formed component and fluid is incompressible.

[5], [6] proved non uniform distribution of polyurethane pressure along the high of the cylindrical specimen which has been pressed in closed dies. Higher values of the pressure were detected near to the top, the lower near to the bottom of the specimen.

Polyurethane has quite visible elastic change of the volume followed by a rapid increase of its deformation resistance. On the contrary to the fluid, a relative motion (slip) of the polyurethane versus tube wall is a reality as the result of clearances compensation and elastic volume changes.

Generated friction forces at the interfacing area, having active sense, help to “carry” the tube material volume into the section of maximal deformation. Active friction forces may thus influence the thinning process of component.

6. CONCLUSION

There was verified process of radial expanding of thin walled tubes with clamped ends up to fracture stage, using polyurethane as a loading medium.
The tests proved to be safe at the moment of the failure and tooling was very simple on the contrary to hydraulic system.
The results of the wall straining analysis were acceptable and verified the availability of elastomer in described tests.
There are prepared bulging tests applying fluid as forming medium to study the possible wall straining deviations and thus the effect of polyurethane.
There was put forth a methodology for definition of material parameters K and n reflecting the biaxial stress state.

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GRANIČNA OBRADIVOST TANKOZIDNIH CEVI

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REZIME

Rad obrađuje problematiku dvoosnog deformisanja tankozidnih cevi i sa tim u vezi granicu obradivosti. Ekperiment jednoosnog naprezanja u ovom slučaju ne daje pravu sliku o vrsti procesa. U literaturi se sreću rešenja ovog problema uz primenu fluida. Rešavanje problema na ovaj način je kompleksno i nepouzdano.

U ovom radu opisana su eksperimentalna istraživanja dvoosnog opterećenja tankozidne cevi pomoću elastičnog alata. Opisani su prvi rezultati ovih istraživanja kao i teorijski pristupi za određivanje naponskog stanja. Jedan od ciljeva rada je bio i definisanje karakteristika materijala cevi kao i vrednosti parametara K i n.

Za razliku od sličnih eksperimenata gde se koristi fluid, ova vrsta istraživanja omogućava jednostavno i pouzdano određivanje prve pukotine u cevi.