MECHANICS OF SQUARE TUBES BENDING AND CROSS SECTION DISTORSION

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The paper deals with characteristics of plasticity and strength of tubes materials. Tested where samples with and without the seam weld, annealed and without annealing. Ideal position of the welded wall was studied with respect to neutral axis shift. This being closely connected with the mode of bending when super imposed forces are added. Analysis of the bending forces mechanics and bending stress distribution was also discussed. Examined were also the cross section distorsions and the stabilizing effect of sharp edges.

Keywords
tube bending, material characteristics, square cross section, weld position, section distorsion, bending forces

1. Introduction

Components made of tubes are typical parts of hollow frame structures, hydraulic systems, sanitary goods, having also a pilot position in lightweight constructions, typical e.g. for automotive and aircraft industry. Here the requirements for material savings and weight reduction are one of the primary significance. Load optimized parts are often characterized by very complex shapes, welded structures and by the use of special materials e.g. [Merklein 2005] [Neugebauer 1999] [Groche 2006]. Prevailing manufacturing methods of complex, often sophisticated components, are hydro-forming technologies as well as conventional bending of tubes and profiles, e.g. [Merklein 2005] [Neugebauer 1999] [Groche 2006].

Following item, dealing with problems of tube bending process, refers to components of smaller diameters or cross-section sizes, e.g. (6 to 50) mm, having relatively thin walls. Available initial semi--products are seam-less tubes or those, produced by continuous roll forming technology and final welding.

The target of this contribution is an analysis of tubes bending hawing square cross-section and a seam weld in the centre line of one wall. Regarding the particular components required, there was studied the possibility to substitute the annealed initial semi-products by non--annealed ones, thus to profit some savings. Moreover, it was required to analyze the cross-section distorsion expected and to define its admissible deviations.

***Figure 1.** Shape of the fifth door hinges*

The three materials seemed to be convenient and recommended: steels EN E235+CR1, EN E190+CR2 and EN E220+CR2, being applied in the design of the fifth door hinges of passenger cars, see fig. 1. Cross-section size of the analyzed square tube component was (20x20x2) mm.

In general, the quality of the bend depends on the
- material characteristics,
- geometry of the component,
- method of bending.

Unbalanced interaction among these influences increases the tendency to failures generation.

Thus the first step was the study of the materials "forming" suitability reflecting the quality of seam weld and its position with respect to the bending plane.

2. Material characteristics

Due to the applied bending technologies and eventual position of the seam weld, when considering e.g. a three dimensional manifold elements, tensile tests seemed to be the most suitable experiments to define the plasticity and strength characteristics of materials in question.

The dog-bone shaped test specimens were acquired from each walls of the tubes, welds were always in the middle line. Three samples for each level of measurement seemed to be sufficient to define the average values of materials characteristics.

Graphical representation of tensile tests results brings fig. 2. Here are apparent differences of strength and ductility among the samples with or without the seam weld (listed values are a numerical average).

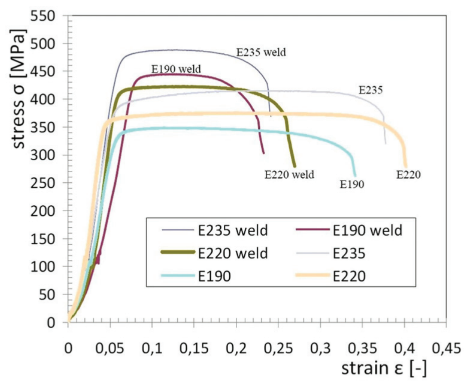


***Figure 2.** Results of tensile test*

Material	$Rp_{0,2}$ [MPa]	Rm [MPa]	A [%]
E235	378,30	418,80	37,0
E235 weld	457,92	488,90	24,3
E190	331,27	349,58	33,0
E190 weld	418,32	424,77	21,5
E220	376,20	392,07	39,5
E220 weld	420,53	433,46	26,4

Survey:
- In general – the samples having the seam weld exhibit lower ductility, but higher strength.
- The steel E220 seems to be the most suitable for the application of non-annealed tubular semi-products for bending. The ductility 26,4% of samples having the weld is a fair value to withstand the elongation of the outer fibres during "sharp" bending of manifold elements (see latter).

– The materials (especially E190 and E220) can be treated as ideally plastic, without work hardening effect. This phenomenon simplifies the choice of bending stress distribution over the cross-section.
– The loss of plastic stability (point of ultimate strength) of presented materials is roughly positioned in the first halves of the flow stress curves. Necking range is thus comparatively long, so that possible crack appearance can be delayed.

3. Geometrical parameters

Next text brings a survey of piece of knowledge relevant to round tube bending. Findings will be used to provide inside into problems of square tube bending. In analysis of round tube bending [Hosford 2007] [Guibert 1960] [Gorbunov 1981] [Kovtun 1964] emphasized two main geometrical parameters:

• s/D … relative thickness of the wall;
• R/D … relative radius of the bend,

where ´s´ is the wall thickness and ´D´ the outer diameter of a tube, ´R´ is the inside radius of the bend.

These parameters have a mutual correlation with the view of quality failures; it means cracks, warpings and ovality generation.

In general: If the bend radius is too sharp (lower R/D), excessive tensile strains on the outside of the surface may cause cracking. Due to the compressive strains on the inside of the bend, buckling (warping) of the inside wall is encountered. Moreover a collapse (ovality) of the tube is an accompanying reality. Mentioned defects are schematized in fig. 3.

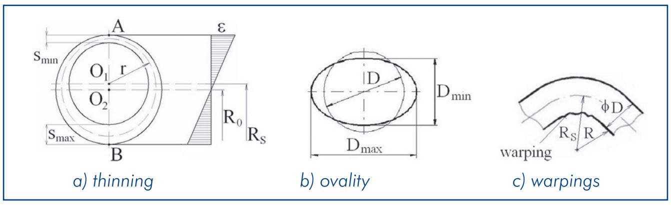


Figure 3. *Failures of round tubes after bending*

The magnitude of s/D defines the boundary between thick tubes and those, having thinner walls, the second group being more inclinable to the loss of geometrical stability of the inside wall. [Guibert 1960] stated the boundary of thin-walled tubes as

$$\frac{s}{D} < \left(\frac{1}{16} \div \frac{1}{20}\right) = (0{,}06 \div 0{,}05) \qquad (1)$$

The sensitivity to the loss of geometrical stability (buckling) is also governed by the magnitude of R/D and by the mode of bending.

To restrain the generation of buckling some types of inserts (e.g. mandrels) are put into the interior of the tubes, to support the inside wall.

– The magnitude R/D > 3 shares good conditions with regard to buckling, when simultaneously s/D > 0,1. In such a case bending can be performed without the mandrel.
– Problems with buckling are encountered when R/D = 2,5 and s/D = (0,06 ÷ 0,075) [Guibert 1960] [Samek 1983] [Elfmark 1992].
– When mandrel is applied, acceptable parameters are R/D = 3 and s/D = 0,05 [Elfmark 1992] [ASM 1969].

With sharp (tight) bends, thinning of the wall is progressive, having the maximum at the point (A) fig. 3a). The change of the wall thickness over the cross-section seems to be fluent with the maximum at the point (B). As a consequence, the neutral axes shifts toward the inside. As implies the linear distribution of engineering strain in fig. 3a), the radius of the mid - plane $R_S \neq R_o$.

As proved by [Kovtun 1964] the fluent change of the wall thickness is a typical phenomenon of round tube bending (see fig. 3a). Here ´r´ denotes the radius of the mean circle of the deformed cross-section. With the assumptions of uniaxial stress and biaxial strain state, having neglected the ovality, [Kovtun 1964] determinate the rules of wall thickness change. When ε_r and ε_L are radial and longitudinal engineering strains, the at the point (A) is e.g. valid

$$\varepsilon_r = -\frac{r}{R}; \qquad \varepsilon_L = \frac{\frac{r}{R}}{1-\frac{r}{R}} \qquad (2)$$

The neutral axes shift and the change of the wall thickness over the cross-section could be implied when determining the internal bending moment.

Note: The above presented considerations refer to a pure bending, without superimposed compressive or tensile force.

Prognoses of failures generation for the given material, mode of bending and process conditions facilitate technological forming limit diagrams (TFLD). Their coordinate system is represented by important geometrical parameters of the formed component. They are closely connected with the severity of straining and are usually implemented in formulae defining the deformation resistance. The fields of good and failed pressings are separated by border lines [Samek 1999].

Well known are TFLD presented by /WOOD/, e.g. [Samek 1999], who applied log-log coordinate system, so that border curves are represented by straight lines. He had determined them for some sheet metal forming operations as for flanging, spinning and also for bending. A typical chart, converted into round tube bending process, illustrates fig. 4.

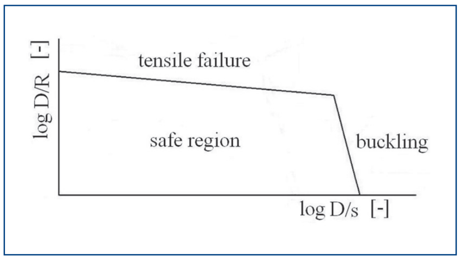


Figure 4. *Technological forming limit diagram (TFLD)*

Buckling on the inside of the bend is governed by D/s ratio primarily, but to some extend depends also on D/R (bend severity). Excessive thinning (necking), finally propagating into cracks, is more sensitive to D/R ratio.

Utilizing this chart for square tubes, then D can be substituted by (h) in terms of the height [Matoušek 2010].

4. Bending of square tubes

4.1. Influence of the seam weld position

Due to the lower ductility of tensile samples the position of welded wall with respect to the plane of the bend is important. In fig. 5 are illustrated three orientations of welded walls including the distribution of the engineering strain. These walls can be positioned
– at the inside of the bend, fig. 5a;
– at he outside of the bend, fig. 5b;
– in the neutral plane where ε = 0, fig. 5c.

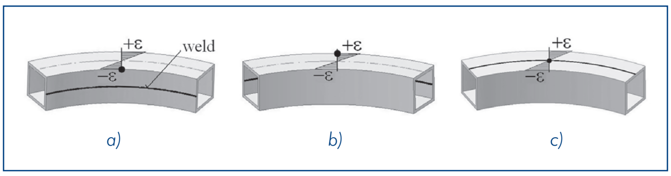


Figure 5. *Correlation between the strain distribution and weld position*

Considering the simplifying assumptions used in the theory of sheet bending [Hosford 2007] [Mellor 1983] [Marciniak 2002] the following formula can be accepted

$$\varepsilon_{max} = \frac{h}{2} \cdot \frac{1}{R_S}, \quad (3)$$

where h is the height of the profile.
When the component has all bends accomplished in one plane, then the ideal position of the welded wall can be guaranteed, see fig. 6 a). Considering three-dimensionally bend components, such an ideal position of the welded wall can be realized only in some section of a complex component, fig. 6 b). Hence, some of the welds can be excessively strained.

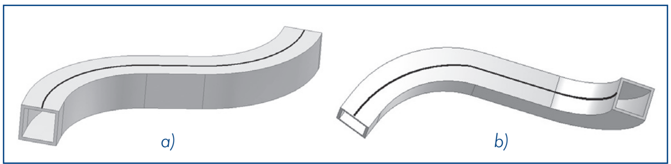


Figure 6. *Plane and three-dimensionally bend*

4.2 Shift of the neutral plane

The bend of a slender rod is accompanied by the cross-section distorsion when a critical value of the slenderness is reached, this being λ = b/h < 3. The shape of the distorsion is illustrated in fig. 7 a). Assuming uniaxial tension, then at points A and B space state of strains is a reality. At the point A the outer fibres tend to move inward, simultaneously is reduced the width. As described more in detail by [Hosford 2007] [Mellor 1983] [Marciniak 2002] the neutral plane shifts from the mid plane towards the inside of the bend to compensate for higher stresses.

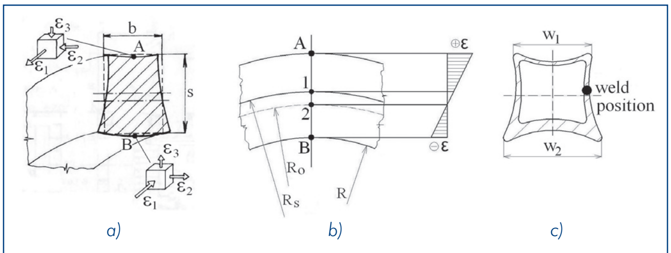


Figure 7. *Shift of the neutral plane*

Round or square tubes have λ = 1, then the space strain state at A and B points can be assumed. On the contrary to rods, tubes are hollow, without the „core". The redistribution of the material volume can be realized only through the walls. The change of the wall thickness of round tube is presented in fig. 3 a) as well as the shift of the neutral point. Due to this fact, irrespective to the ideal position of the welded wall of square tubes mentioned above, the weld remains above the neutral point and is stretched (see fig. 7 c). As assumed, the strain was plane strain and bending was realised by pure bending (without superimposed forces in axial direction).

Note: Some authors, as stated in [Samek 1983], assumed space state of strains when bending round tubes, axial, radial and tangential one, the last along the mean radius ´r´. Nevertheless, as proved, the change of the thickness was also fluent and the influence of the state of strains on ovality generation was clarified.

The cross-section distorsion of square tubes, presented in fig. 7 c) represents the actual changes of the shape, proved by measurement, as described later. Bending parameters listed in fig. 1, are conforming to the conditions of sharp bends. The bending process accomplished was not a pure bending, tensile or compressive forces were superimposed and friction under the wiper and pressure bar imparted further effects (see fig. 11).

At this state of the research can be shortly stated, that the change of the wall thickness is not fluent and the shift of the neutral plane is veritable. Analogous to the round tubes, the weld remains above the neutral point and is stretched.

4.3. Bending stress

The choice of bending stress distribution on the tube section reflects the tensile test results listed in the fig. 1. Owing to the small differences between the yield and ultimate stress, work hardening can be neglected for the simplification of engineering calculations. Elastic-perfectly plastic material model is considered, enabling also „spring-back"definition. The linear approximation of the flow stress shows fig. 8.

The range denoted by φ_a corresponds to higher values of relative radii R/h. The range φ_b refers to sharp bends (small values R/h).

As mentioned earlier, the bending parameters, listed in fig. 1, are conforming to the conditions of the sharp bend. That is why the range b) is the applicable part of the chart in fig. 8. In neglecting the neutral axis shift, the stress distribution b) in fig. 8 is likely, giving so called fully plastic moment [Gorbunov 1981]:

$$Mo = \sigma_K \cdot S_M, \quad (4)$$

where S_M is the linear moment of the cross-section.

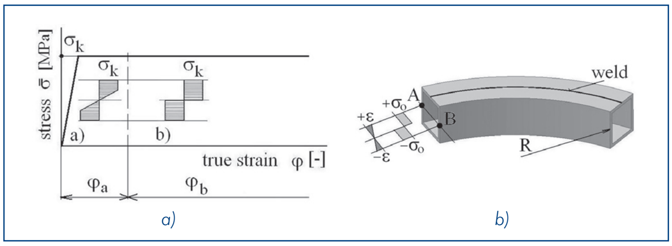


Figure 8. *Linear approximation of the flow stress*

5. Methodology of experiments

5.1 Description of specimens

The geometry of tested specimens is reflects the real components of a passenger car structure. As illustrated in fig. 1, the bend is oriented in one plane, so that the position of the welded wall is ideal.

Tested were:
– three positions of the welded wall, see fig. 5;
– three types of the materials, see fig. 1;
– two radii of the bend predominately.

The fig. 1 brings the technological specification of the 6 specimens from the set of 35 samples having been tested. Symbol N denotes not annealed initial semi products, ´R´ is the inside radius of the components. Bending was performed on the UNISON MG2790 bending machine, which enables the application of three bending modes:
– wrap bending using the swivel clamp;
– draw bending by means of a rotating die;
– compressive bending using thrust axial force.

specimen	material	weld position	R [mm]	R_S [mm]	bending angle
21	E190	neutral plane	57	67	153
24	E220	neutral plane	57	67	153
27	E235+N	neutral plane	57	67	153
30	E190	neutral plane	131	141	55
33	E220	neutral plane	131	141	55
36	E235+N	neutral plane	131	141	55

Table 1. *Technological specification of tested components*

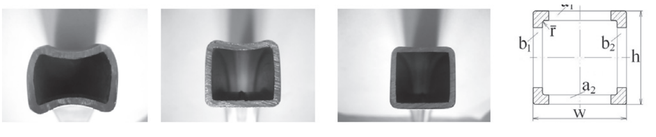
Reflecting the manufacturing processes of examined components, draw and compressive bending modes were applied in experiments (see fig. 11 and fig. 12).

The specimens

No. 21–27…R/h = 57/20 = 2,85 – draw bending with a metallic mandrel

No. 30–36 …R/h 131/20= 6,5 – compressive bending without a mandrel

To clarify the way of the section distorsion during a severe bend, some additional bending test was performed, here the ratio R/h = 21/20 was applies and the interior of the tube was filled with hydrogen peroxide. The shape of the distorsion is shown in fig. 9.



a) R = 21mm b) = 57mm c) R = 131mm d)

Figure 9. *Photography of cross-section distorsion and denotation of edges*

5.2 Changes of the section shape and wall thickness

The wall thickness was measured at 7 points denoted in fig. 10. The values, plotted in the chart proved thinning between points 0 ÷ 3 and increase of the thickness between 3,5 ÷ 6 as expected.

The change of the wall thickness is not fluent. The sharp edges restrict the transfer of material volume to the inside of the bend. In the space of the edges is trapped a certain capacity of material, increasing thus the non-uniformity of the wall thickness. The edges exhibit a stabilising effect to buckling.

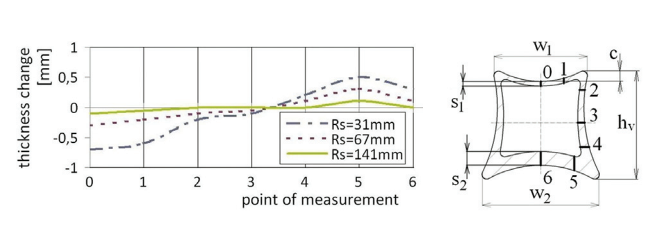


Figure 10. *Course of the wall thickness change*

Due to the above mentioned evidence, the shift of the neutral plane is a reality. The weld, as shown in fig. 7b) is beyond the neutral plane.

The quality of the mentioned components is in practice evaluated by random measurement of the height ´h_v´ and by the value of the outside wall concave deflection ´c´.

To define accurately the concave deflections of all walls, there were measured many values of ´c´ over the circumference of the cross-section applying the device Zeiss Helos. The values, with more detailed graphical description are in [Matousek 2010].

It can be stated, that the value s/h = 0,1 represent more or less thick wall tubes, having the „border" magnitude.

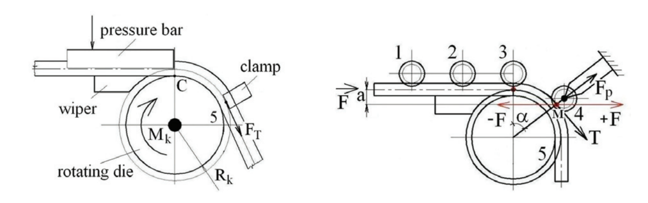
Note: The new, improved analysis of the straining over the circumference is planed exploiting specimens provided with a strain grid.

6. Modes of bending

Fig. 11 represents the sketch of the draw bending method. In general bending moment of outer forces must be balanced by the internal moment $(M_o)_i$ reflecting the final stress distribution over the section. The external force

$$F_T = \frac{M_k}{R_k}, \tag{5}$$

where M_k is the torque moment. Additional forces due to the friction are not considered.



a) draw bending *b) compressive bending*

Figure 11. *Modes of bending*

Assumptions:

a high value of the tensile force F_T;

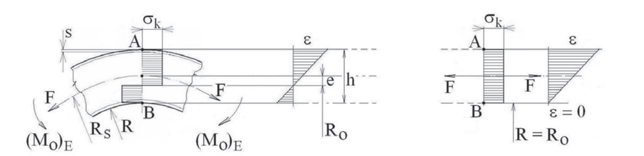
the application of the sharp bend (fully plastic domain);

elastic-perfectly plastic material;

external force F_T acting in the mid-plane;

linear distribution of engineering strain.

Two possible distributions of stresses (in the section at the point ´C´) are illustrated in fig. 12.



a) $(M_o)_E + M_F = (M_o)_i$ b) $(M_o)_E \equiv M_F = (M_o)_i$

Figure 12. *Distribution of stresses and engineering strains*

The case 12a) reflects the situation, when the tensile force F_T has a smaller magnitude, but its effect shifts the neutral plane to the inside, (e) is the value of the shift.

$$M_F = F_T \cdot e\,. \tag{6}$$

The case 12b) reflects the existence of high magnitude of F_T, at the moment when the value e = h/2, while R_o = R, the maximum strain at the outside of the bend is ε_{max} = h/R. Then all bending effect is done by the

$$M_F = F_T \cdot \frac{h}{2}\,. \tag{7}$$

In both cases, if the weld is positioned in the mid plane, it is always stretched.

Fig. 11b) illuminates the principle of compressive bending. The first step of the procedure was wrapping of the tube by swivel of the pressing roller into the position denoted by angle ´α´. The second step was the application of the external, compressive force F which pushed the tube forward, into the focus of bending, which is bellow the roll 3.

In short – the resultant distribution of internal bending stresses is opposite to that in fig. 12. Due to the shift of the neutral plane to the outside of the bend, caused by compressive force, the weld will be loaded by compressive strain.

7. Conclusions

- The materials (especially E190 and E220) can be treated as ideally plastic;
- The samples, having the seam weld, exhibit lower ductility, but higher strength;
- The ideal position of the welded wall can be realized only in some section of a complex component. Hence, some of the welds can be excessively strained;
- The change of the wall thickness was proved, resulting in the shift of the neutral plane;

– The weld may remain above or bellow the neutral point in dependence on the mode of bending;
– The change of the wall thickness is not fluent, which is multiplied by edges;
– The sharp edges restrict the transfer of material volume;
– The trapped material in the space of edges increases the resistance to buckling;
– The concave deflections of all walls are the way of the geometrical stability loss.

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