GEOMETRICAL PHENOMENA IN TUBE BENDING WITH LOCAL INDUCTION HEATING

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Abstract

A theoretical and experimental analysis of a heat induction bending process for tubes used in the power industry was performed. First, the design of the heat induction tube bending process is described and the industrial application areas for this technology are presented. The main methods for tube bending with local induction heating are discussed and the effect of the technology on geometrical parameters of the bends formed is presented. Next, using numerical techniques (FEM), the heat induction tube bending process is modelled. The simulations were performed in a three-dimensional strain state, with thermal phenomena included, using commercial software package Simufact Forming v. 11.0. In the computations, the variations of semi-finished product geometry in the region of a bend being made (cross section ovalisation, darkening and thickening of walls, neutral layer position) were examined. Also, the potential occurrence of phenomena that would limit the stability of the bending process and cause shape defects was predicted. The results obtained from the numerical modelling were then compared to the geometry of bends produced under industrial conditions.

Keywords: tube bending, induction heating, FEM

1. INTRODUCTION

Bent tubular elements are widely used almost in every branch of the market. There are especially strict requirements that should be met by bent elements which are used in the power industry [1]. High strength parameters of such tube bends are required, similar to those of undeformed tube sections. Requirements concerning the geometrical conditions are also much bigger in comparison with the primary products used in other branches of the economy.

Currently a number of methods for tube bending are used, depending on the temperature of process conduction. The processes can be divided into cold bending and hot bending [2,3]. The choice of a proper technology depends mainly on the target application of a final product and its working conditions. The precision and quality of bending, however, depends mainly on the geometrical parameters of the process, particularly on the relative bending radius R, the wall thickness of bent tube g and the applied equipment.

The majority of current bending methods allows for forming the tube bends in a wide range of bend radius and wall thickness while maintaining high geometrical and strength parameters. The limitation here is the maximum diameter of bent tubes. That is why, for tubes with big diameters (more than 300 mm) with relatively small radius (mainly used in the power industry), some unconventional methods of forming bends are applied. Among those methods there are, inter alia, bending processes with local induction heating which, apart from the possibility to form bends with large cross-sections, allow also for achievement of products with high strength and geometrical parameters. It should be underlined, however, that these are relatively new processes (developed in the 80s of 20th century) and have not been fully mastered or tested.

2. THE NATURE OF INDUCTION TUBE BENDING

The diagram of induction tube bending is presented in **Fig. 1**. A tube is fixed from one side in the gripping jaw of a rotary arm (7) which is used for setting the bending radius. The second tube end is clamped in the gripping jaw of a pusher (1) which can move only along the tube axis. During bending the tube is heated locally on a relatively small length by a ring-shaped inductor (6) while the pusher moves the tube along its axis towards the rotary arm. As a result, the bend is formed directly in the area of heating without plastic deformation of the remaining tube fragments because the flow stress of a heated material is lower than the flow stress of unheated regions [4,5].

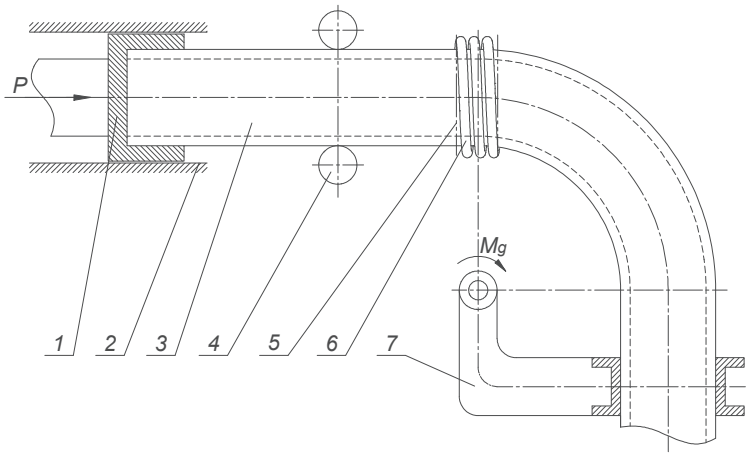

Fig. 1 A schematic representation of tube bending with induction heating: 1 - pusher with the gripping jaw, 2 - slide bars, 3 - bent tube, 4 - guiding rollers, 5 - the local area of heating and forming, 6 - inductor, 7 - forming arm with the gripping mechanism, *P* - pushing force, *Mg* - bending moment

In comparison to conventional tube bending, induction tube bending is characterised with a number of advantages, including, first and foremost, significantly bigger technological possibilities (bending tubes with diameter from 300 mm up to 1600 mm) and the possibility to achieve relatively small values of bending radius with small deformation of cross-section. The main disadvantage of this technology is big energy consumption (bending lasts a few to more than 10 hours) which causes bigger energy use in comparison to other bending methods.

3. FEM MODELLING OF INDUCTION TUBE BENDING

In order to determine the phenomena occurring in the deformed area during induction tube bending a numeric simulation was conducted for the 16Mo3 steel tube with diameter D = 355.6 mm and wall thickness g = 36 mm, for which the bending radius was R = 533.4 mm. The tube was modelled with the use of eight-node shell elements of Solid Shell type. The geometry of bent pipes as well as the distributions of effective strain, stress, temperature and fracture criterion were analysed.

Commercial package software Simufact Forming version 11.0 was used for simulation of tube bending. This software was used many times by the authors for numerical modelling of complex metal forming processes and the achieved results were positively verified in experiments [6,7]. The analysis was conducted in a three-dimensional state of strain, taking into account the thermal phenomena. It allowed for modelling of both bending as well as local heating and cooling of the tube. The geometrical model of tube bending with the local induction heating, prepared for the purpose of conducted calculations, is shown in **Fig. 2**.

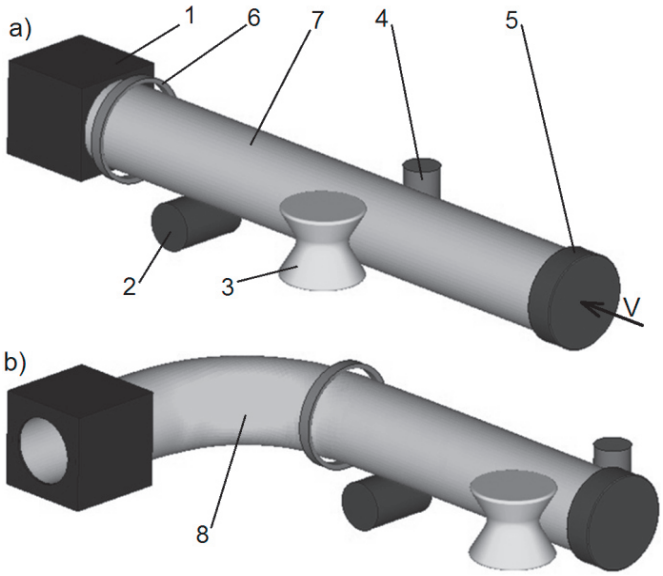

Fig. 2 Geometrical model of induction tube bending at: a) the start of the process, b) the end of the process; 1- gripping jaw, 2, 3, 4 - guiding rollers, 5 - pusher, 6 - ring-shaped inductor, 7- tube, 8 - tube bend

Steel 16Mo3 is widely applied in the power industry, e.g. for pipelines transporting hot fluids and steam [8]. It is characterised with high strength properties, good corrosion resistance and good heat resistance. Moreover, it can be easily welded with the use of conventional methods and typical welding materials [9]. Elastic-plastic material model of 16Mo3 steel was prepared on the basis of plastometric compression tests. It was assumed, that the tube will be locally heated through (along the section of about 60 mm) to a bending temperature which is 900 °C. Additionally, it was assumed in calculations that the temperature of tools (gripping jaw, rollers and pusher) is constant: $T = 20$ °C. The remaining parameters of the process are: friction coefficient between the tube and the tools $m = 0.1$ (constant friction model), heat transfer coefficient between the material and the tool - 10 kW/(m^2·K), heat transfer coefficient between the heating ring and the tube - 100 kW/(m^2·K) and between the material and the ambient air - 3 kW/(m^2·K) (for cooling with air stream).

The geometry of the tube bend and the effective strain distribution obtained in simulation is shown in **Fig. 3**. A characteristic phenomenon during tube bending is the change of wall thickness in cross-section of the tube bend. It is caused by the occurrence of different stresses in the cross-section of the bent element. According to **Fig. 3**, in the area of inner radius the materials is compressed and thus the wall thickness significantly increases. At the same time in the area of outer radius the material is stretched and as a result the wall is thinned. Observed changes of wall thickness are quite big and result from geometry of the tube being bent (big wall thickness in reference to the tube diameter). During tube bending with local heating a shift of neutral axis can be observed towards the outer radius of geometrical axis of the bent curve (in the analysed case the shift equalled about 10 mm). It is a phenomenon contrary to the one occurring during conventional tube bending methods and results from kinematics of the process in which the bending moment is formed as a result of the influence of axial force applied to the non-deformable tube end.

Bending tubes is always accompanied by deformation of cross-section (ovalisation). However, it should be pointed out here that deformation of a profile during induction bending is significantly smaller than during tube bending with the use of other methods.

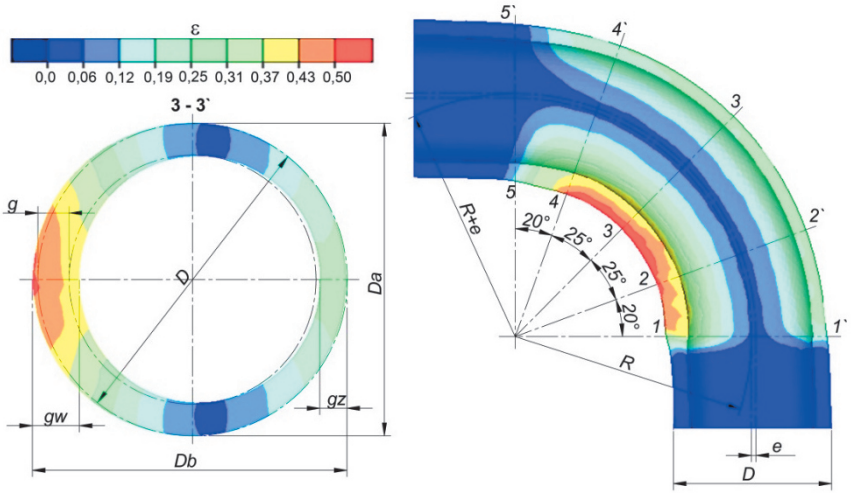

Fig. 3 Geometry of the tube bend with distribution of the effective strain, determined by the finite element method (FEM)

In order to assess the changes in the tube shape, diameter and wall thickness at the five characteristic sections (**Fig. 3**) were measured within the bent area. Results of the measurements for the geometry determined by the finite element method (FEM), as well as for the bends formed in industrial conditions, are summarized in **Table 1**. The data presented therein confirm the earlier observation regarding the slight deformation in the cross-section of the bent elbow. The determined average value of cross-sectional ovalization is, respectively, about 2% for the bend obtained from the calculations, and about 3% for the bends in industrial conditions. These values are several times lower than the permissible limits (as defined in the EN 12952 and PN EN 13480 standards).

Table 1 Geometric parameters of induction bending of 16Mo3 steel tube, obtained during the FEM simulation (verses A) and the industrial tests (verses B)

Geometric features of the tube tube diameter D = 355.6 mm, tube wall thickness g = 36 mm,							
Geometric features of the bend bending radius R = 533.4 mm, shift of the neutral axis e = 10.2 mm							
Bend cross-section No.		1-1	2-2	3-3	4-4	5-5	Average value
Wall thickness in the bend tension zone g_w (mm)	A	46.2	51.5	52.5	51.2	41.8	48.64
	B	41.9	52.9	53.6	53.1	36.9	47.68
Wall thickness in the bend compression zone g_z (mm)	A	31.4	30.2	30.1	30.7	34.9	31.46
	B	32.7	30.5	30.0	29.4	33.1	31.14
Ellipse major axis D_b (mm)	A	361.5	359.5	360.9	359.1	356.7	359.54
	B	359.3	364.0	365.1	362.2	360.9	362.3
Ellipse minor axis D_a (mm)	A	356	352.8	353.2	351.8	348.9	352.54
	B	354.4	348.9	347.3	350.2	356.8	351.52
Cross-sectional ovalization $e = \frac{D_a - D_b}{D} \cdot 100\%$	A	1.55	1.88	2.16	2.05	2.19	1.97
	B	1.38	4.24	5.00	3.37	1.15	3.03

The distributions of effective strain, stress, temperature and fracture criterion are shown in **Fig. 4**. When analyzing the distribution of strain (**Fig. 3** and **Fig. 4a**), its considerable non-uniformity can be observed. The greatest strain occurs in the inner radius zone where deformation of material includes practically the entire wall thickness. On the opposite side, in the outer radius zone, the values of strain are twice smaller, while in the area of the neutral axis, they are close to zero. The large non-uniformity of strain in the bending area will affect the strength parameters of tube bends. Therefore, the bending process is always followed by heat treatment.

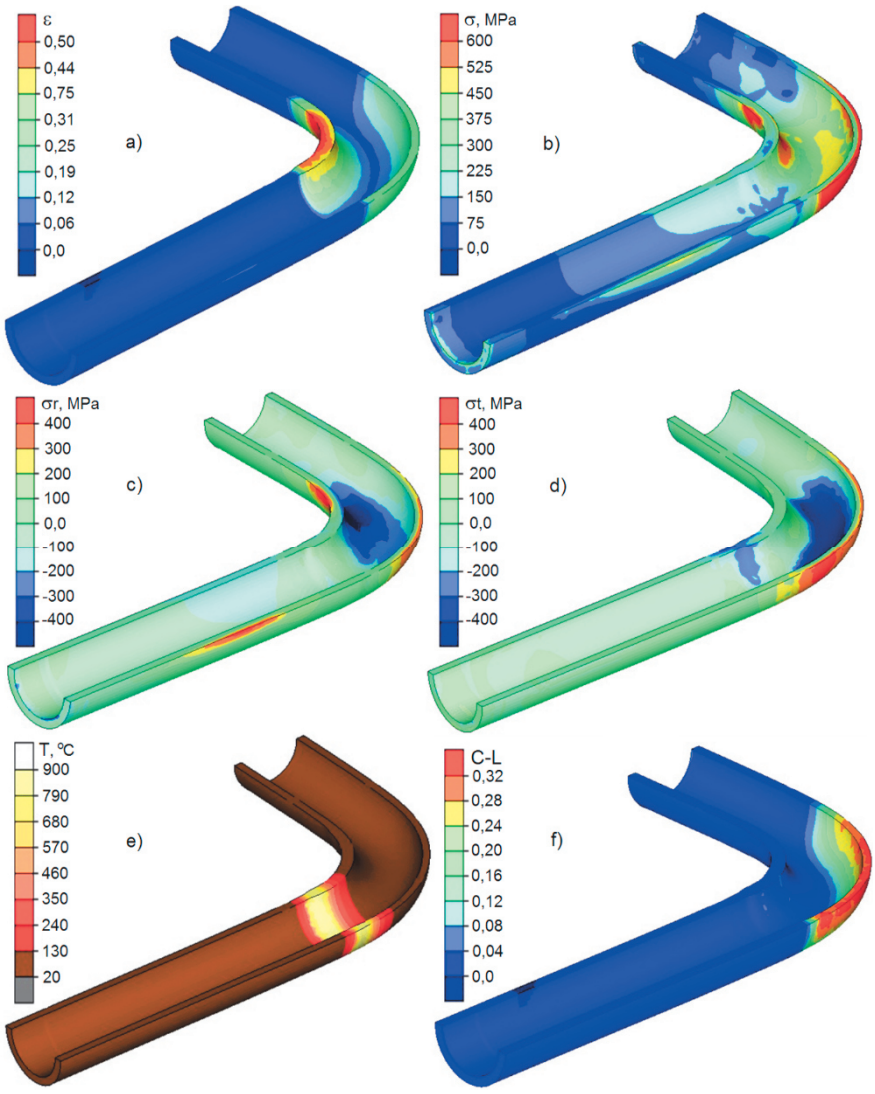

Fig. 4 Distributions of: a) effective strain, b) effective stress c) radial stress, d) hoop stress, e) temperature, f) Cockroft-Latham fracture criterion, determined by means of the FEM simulation at the final stage of bending

The effective stress distribution is also characterized by large non-uniformity (**Fig. 4b**). The highest values of the effective stress are located in the vicinity of the outer and inner radii of the tube being bent. However, they are local (surface) stresses by their range. In the zone of outer bending radius, the area of maximum stresses is much larger than the area of extreme stresses in the vicinity of the inner radius. Moreover, in the inner radius zone, they will be compressive stresses, and in the outer radius, they will be tensile stresses. To better illustrate the nature of the stresses occurring during the tube bending process, distributions of the radial stress (**Fig. 4c**)

and hoop stress (**Fig. 4d**) in the bending zone were determined. As expected, the greatest radial and hoop tensile stresses (with positive sign) are located in the area of the outer radius of the bent area, while the compressive stresses (with negative sign) dominate in the inner radius zone. As a result, a much greater effort of material occurs in the outer radius area during bending. Under unfavorable conditions, this may be the cause of material cracking in this zone.

In the induction tube bending processes, the temperature is a factor that initiates forming because it reduces the flow stress in the bending zone, so that the material is deformed at a relatively short length, thus making it possible to obtain bends with high geometrical parameters. According to **Fig. 4e**, the temperature in the forming zone has layered distribution. Directly within the inductor, the temperature reaches the maximum value (about 890 °C). Then, as the distance from the inductor increases, it rapidly drops until it reaches the ambient temperature. When analyzing the distribution of the Cockroft-Latham failure criterion (**Fig. 4f**), its highest values can be observed in the zone of outer radius of the bent area. The highest values of tensile stresses are located in this area, which can lead to cracking of the material. It can be noted however that the extreme values of Cockroft-Latham integral are relatively small (about 0.3). For the typical structural steels, the Cockroft-Latham criterion limits vary within the range of 0.7 ÷ 1 [10, 11]. On this basis, it can be concluded that there should be no cracking of the material during bending.

3. INDUSTRIAL INDUCTION TUBE BENDING TESTS

Industrial tube bending tests for power engineering applications were performed at the power engineering repair plant of Zakłady Remontowe Energetyki (ZRE) Katowice S.A. The tests were carried out using the PB1200R induction bending machine, which is installed there and which allows bending a variety of tubes with diameter ranging from 168.3 mm to 1220 mm and wall thickness from 5 mm to 100 mm. Additionally, the machine is able to form bends in a fairly wide range of bending angles - from 0° to 180°, as well as spatially, using the 3D system. A typical induction tube bending, conducted at ZRE Katowice S.A., is shown in **Fig. 5**. It corresponds to the FEM model presented in the paper.

Fig. 5 Induction tube bending at ZRE Katowice S.A.

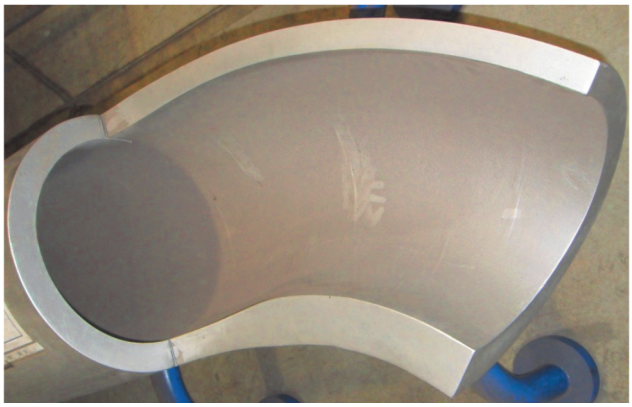

Fig. 6 Axial section of the tube bend formed during industrial tests

During the induction tube bending, no phenomena disturbing the process were observed, and the resulting geometry of the bent elbow was free from defects. To determine the deformation of the tube cross-section, measurements of diameters and wall thicknesses of the formed bend were conducted in accordance with **Fig. 3**, their results being presented in **Table 1**. The axial section of the tube bend formed in the industrial conditions is shown in **Fig. 6**. A close geometrical similarity is visible between the product bent in the industrial conditions and the outline determined during the FEM numerical analysis. The observed variations in the wall thickness

of the formed bend are within the range accepted by the relevant standards, and the resulting cross-sectional deformation (ovalization) is more than three times lower than the permissible limit value.

SUMMARY AND CONCLUSIONS

The performed numerical calculations of the induction tube bending process showed that conducting pre-implementation analysis in the computer virtual space is fully justified. Such analysis will allow determining the optimal process parameters to ensure obtainment of tube bends with geometrical parameters that meet the requirements of the Office of Technical Inspection (UDT). Thanks to the simulations, the geometry of bent tubes was determined, as well as the distributions of effective strain, stresses, temperature and fracture criterion. The obtained results were experimentally verified in the industrial conditions. As a result of the performed tests, it was found that:

- numerical modeling of induction tube bending is possible;
- tube bending with local induction heating allows tube bends with accurate geometrical parameters to be formed;
- high concordance between the results of numerical analyses and industrial tests was observed;
- a characteristic feature of induction tube bending is a shift of the neutral axis toward the outer radius, contrary to other bending processes, where the neutral axis moves toward the inner radius;
- simulations revealed large non-uniformity in the distribution of strain, stress, temperature and the fracture criterion in the bent tube;
- it is advisable to conduct further research in order to determine the specific relationships between the parameters of induction bending process and the parameters of obtained tube bends.

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