PLASTOMETRIC TESTING AS A BASIS FOR NUMERICAL ANALYSIS OF THE TUBE BENDING PROCESS

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Abstract

This paper provides a discussion on results of plastometric tests of selected steel grades used to manufacture pipeline components for the power engineering applications as well as for the gas and petroleum industry The formability assessment was conducted under compression conditions using a thermal-mechanical Gleeble simulator. Studies on the dependence of flow stress σ_p on strain *e* were conducted at the temperature ranging from 20 to 1100 °C and the strain rate of 1 s^{-1}. The deformation characteristics established for steel were implemented in numerical simulations of the tube bending process with application of local induction heating.

Keywords: Gleeble simulator, plastometric tests, tube bending, numerical simulations

1. INTRODUCTION

Dynamic development of computer technology as well as of computer software for designing of metal forming processes based on the finite element method has triggered demand for a description of mechanical properties of material subject to plastic deformation. Characteristics of material deformation obtained under conditions of plastometric testing provide grounds for developing constitutive equations in the form of $\sigma_p = f(e, T, \dot{e})$.

Studies devoted to determination of formability of materials are oriented towards development of fundamental experimental techniques and mathematical functions establishing dependences between flow stress as well as deformation limit and deformation parameters [1].

The most common and popular methods of formability assessment include tests of tension, compression, torsion and impact as well as model tests of upsetting and rolling. The plastometric testing methods being applied should ensure that metal forming conditions are recreated or at least made as similar to the actual ones as possible.

The methods used for determination of formability characteristics and deformation behaviour of materials evolve on an ongoing basis. The foregoing is triggered by the dynamic development of both the knowledge on plastic deformation as well as the related technology, which enables upgrading of testing stations. The evolution of information technologies and electronics cause that the contemporary equipment for plastometric testing features increasingly advanced computer control systems, test result recording systems and programs for data analysis and processing. Torsion is mainly investigated using torsional plastometers. Under compression tests, deformation dilatometers and "Gleeble" testing systems are becoming increasingly common [2].

This paper provides a discussion on results of plastometric tests of selected steel grades used to manufacture pipeline components for power engineering applications (X10CrMoVNb9-1, 14MoV6-3, 10CrMo9-10) as well as for the gas and petroleum industry (L485ME). The formability assessment was conducted under conditions of compression, using a thermal-mechanical Gleeble simulator on stock at the Technical University of Ostrava [3, 4]. Studies on the dependence of flow stress σ_p from deformation *e* were conducted at the temperature ranging from 20 to 1100 °C and the strain rate of 1 s^{-1}. The characteristics thus obtained were implemented in numerical simulations of the process of tube bending with local induction heating.

2. UNIAXIAL COMPRESSION TESTS

The plastometric hot compression tests were conducted using samples of 10 mm in diameter and 12 mm in height. The samples were heated to a pre-set deformation temperature, soaked at this temperature for 30 seconds, and then compressed to obtain a half of the original height, which corresponded to the actual strain of 0.7. The dependence of flow stress σ_p [MPa] from deformation ε [-] was determined based on the value of the force acting on the sample, as recorded in the compression test, as well as the current sample height on the pre-set strain rate. The flow stress characteristics were established assuming frictionless compression based on the following formulas:

$$\sigma_p = \frac{4F \cdot h_1}{\pi \cdot d_0^2 \cdot h_0} \tag{1}$$

and

$$e = \ln \frac{h_1}{h_0} \quad . \tag{2}$$

For the steel grades studied, the dependence of flow stress from deformation σ_p = f(e, T) on different compression temperatures has been illustrated in **Figure 1**.

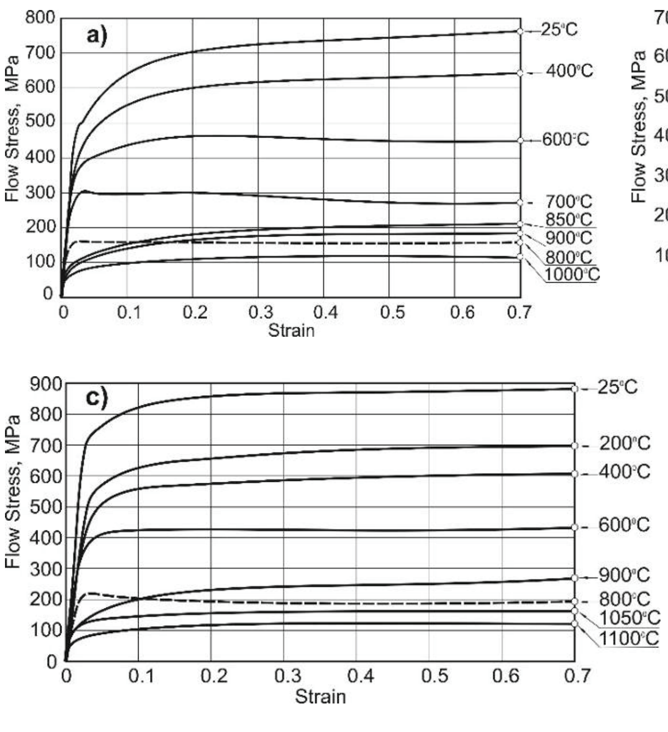

Figure 1 Flow stress σ_p in the function of deformation e for steel grades:
a) 10CrMo9-10, **b)** 14MoV6-3, **c)** X10CrMoVNb9-1, **d)** L485ME

The flow curve characteristics of the steel grades studied feature characteristic and similar courses. Within the range of cold deformation temperatures, i.e. from ambient temperature up to 400 °C, flow stress increases continuously as deformation rises. On the other hand, within the temperature range of 600÷700°C, one can observe a distinctive flow stress peak followed by its decline beyond the peak, this being conditioned by processes of recovery and dynamic recrystallisation. At a temperature exceeding 700 °C, the course of flow characteristics observed is determined by phase transition starting temperature Ac_1 and finishing temperature Ac_3. For the chosen steel grade, i.e. X10CrMoVNb9-1, the range in which phase transition proceeds has been illustrated in the CCT diagram provided in **Figure 2**. The effect of phase transition on the value of maximum flow stress σ_{max} [MPa] dependent on temperature has been depicted in **Figure 3**.

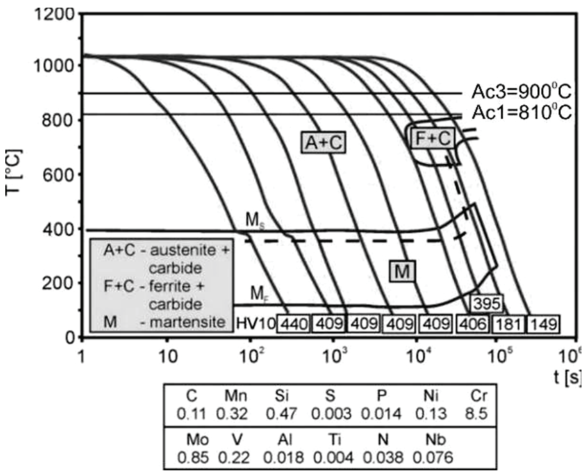

Figure 2 CCT diagrams for the X10CrMoVNb9-1 steel [5]

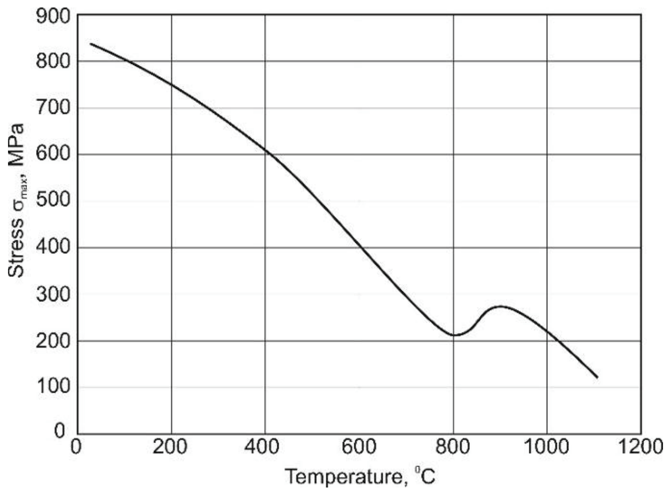

Figure 3 Maximum flow stress σ_{max} depending on temperature for the X10CrMoVNb9-1 steel

3. NUMERICAL MODELLING OF THE BENDING PROCESS

Bending tubes of large diameters and small bending radii is performed with tube benders featuring local induction heating [6]. Operating characteristics of bends produced by this method are mainly conditioned by appropriate choice of process parameters, i.e. temperature, forming rate and cooling conditions in the course of bending. Optimum parameters of the process can be defined through multi-variant numerical modelling (**Figure 4**) entailing differentiated heating temperature and tube feed rate in the course of bending [7÷9]. In order to acquire reliable results of the bending process simulation, in the numerical calculations, one must use material models based on plastometric tests. The purpose of the numerical analyses conducted was to make a selection of process parameters ensuring geometric features of the bends to be produced conforming with the applicable standard, i.e. suitable wall thickness in the zone subject to tension and compression as well as cross-section ovalisation [10÷13]. The article provides a discussion on selected results of numerical simulations conducted for one of the said materials, namely the X10CrMoVNb9-1 steel, for which flow stress characteristics were determined.

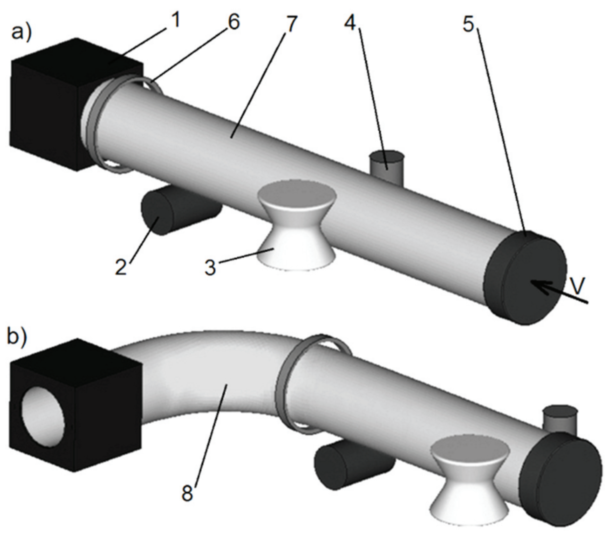

Figure 4 Geometrical model of induction bending of tubes: **a)** process start, **b)** process end; 1 - clamp, 2 - bottom support roller, 3 - smooth roller, 4 - profile roller, 5 - pusher, 6 - heating ring, 7 - tube, 8 - completed tube bend

The numerical simulations of the tube bending process involved different tube heating temperatures, tube feed rate being altered and diversified conditions of tube cooling outside the bending zone. In calculations, the flow stress characteristics in the function of deformation, as determined by means of the Gleeble simulator, were used (**Figure 1**).

The said calculations were conducted by application of the finite element method (FEM) using version 11.0 of the Simufact Forming software [10]. The numerical simulations were based on an assumption that the tube would be heated straight through up to the forming temperature. The initial temperature assumed for the tube and for tools was 20 °C. The assumed coefficient of heat transfer between the tube and the environment equaled 0.35 kW / m²·K for still air cooling and 4 kW / m²·K for forced water-spray cooling.

Results of the numerical simulations of bending of a tube with the dimensions of Ø 510 x 80 mm for the calculation variant involving the bending radius of R=1325 mm, heating temperature of 950 °C, tube feed rate of v = 4.5 mm / min and free cooling in air have been collated in **Figures 5 - 7** and in **Table 1**.

Figure 5 shows the geometry of the tube bend cross-section, whereas **Table 1** provides a comparison of the bend's geometric parameters calculated by application of the finite element method, entailing the quantities defined as criteria in standard [11]. **Figure 6** shows distributions of deformation intensity, substitute stresses, radial stresses, peripheral stresses, temperature and the Cockroft-Latham criterion [14÷16] of fracturing on the tube bend surface. **Figure 7**, on the other hand, depicts the course of force at the pusher during the tube bending for different pusher velocities and cooling conditions past the tube heating zone.

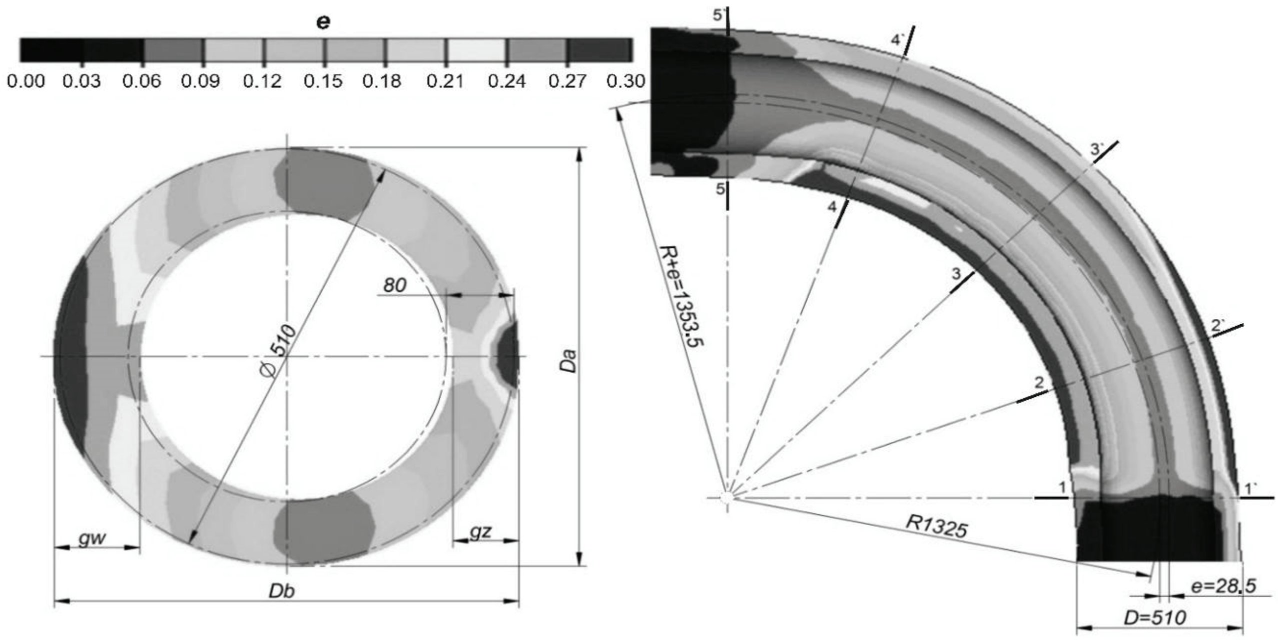

Figure 5 Tube bend cross-section geometry determined by FEM

Table 1 Comparison of FEM-based computational geometric features of the tube bend with normative values

Tube bend geometry	Tube wall thickness, mm		Cross-section ovalisation, % $e = \frac{2(D_a - D_b)}{D_a + D_b}$
	Compressed zone g_w	Tensioned zone g_z	
FEM simulation	73.6	95.6	0.92
Standard requirements [10]	min. 60.0	min. 72.0	max. 8.0

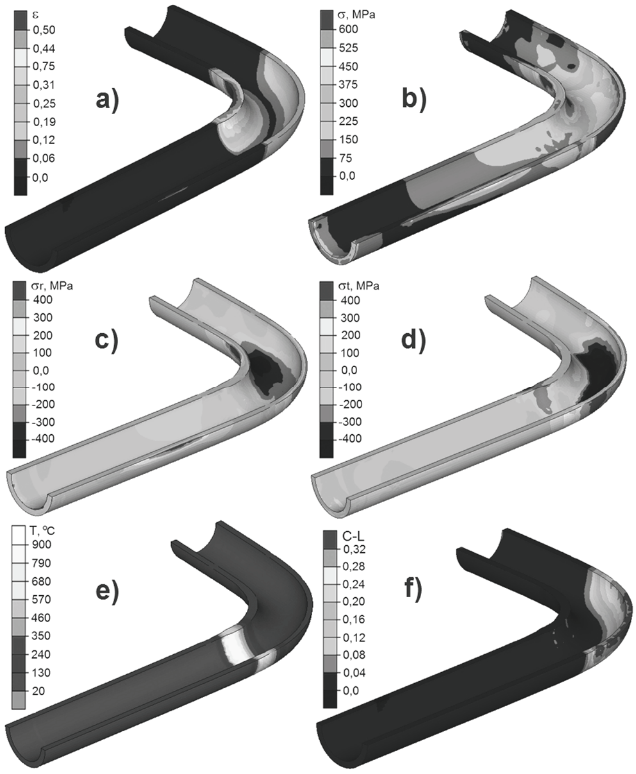

Figure 6 FEM-based distributions of: **a)** deformation intensity, **b)** substitute stresses, **c)** radial stresses, **d)** peripheral stresses, **e)** temperature, **f)** Cockroft-Latham fracture criterion

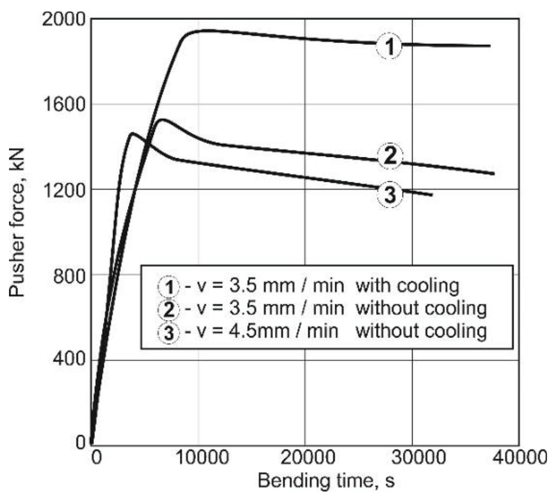

Figure 7 Course of force at the tube pusher during tube bending

4. CONCLUSION

The bending technology discussed, developed in 1980s and involving application of induction heating, is relatively new, and not all of its aspects have been completely mastered and examined yet. Numerical modeling of processes of tube bending enables optimization of bending parameters which, in turn, allows for bends of highly valued geometric features conforming with the applicable standards to be formed. The basic parameters used in numerical models of the tube bending process are the characteristics of material formability established at different temperatures. Acquired from plastometric compression tests, these characteristics, when combined with an analysis of CCT diagrams, make it possible to take the effect of phase transitions on flow stress into consideration. This may provide grounds for defining the optimum bending process temperature.

The results obtained from numerical process simulations may be used under industrial conditions, thus enabling reduction of the costs involved in the technology implementation without the necessity of adjusting the parameters of bending in industrial tests.

ACKNOWLEDGEMENTS

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