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Evaluation of Material Deformation During Process of Precise Carbon Steel Tube Cold Draw Forming

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Abstract. A cold forming technology (cold drawing) produces precise seamless tubes, which can be found in various industries and applications. A high shape accuracy is achieved while the material is reinforced due to plastic deformation during cold forming. The reinforcement of the material in the forming process largely depends on the degree of deformation and plastic properties of the material. The purpose of this study is to compare results of stereological methods used in metallography with data from FEM simulation obtained using software DEFORM and Lagrangian method. Values of strain obtained experimentally and by FEM simulations are supplemented by results of Vickers hardness measurements and mechanical properties obtained by tensile testing after each cold draw operation.

1. Introduction

Cold forming is widely applied process in industrial production. High-quality tubes under acceptable economic conditions are manufactured by draw process. To achieve the final diameter and wall thickness of tubes this process is reduced successively to several cold drawing steps. Draw process can be done by either drawing the tube through a die and adding a plug, which results in better-defined surface quality. As a feedstock for cold drawing is usually used the hot rolled tube. During subsequent drawing steps, the tube undergoes plastic deformation, generating residual stresses and strain. Palkowski at al. [1] investigated residual stress state of drawn tubes by numerical simulation and neutron diffraction analysis. The material of drawing tube was a cooper. Neves at al. [2] were looking for the best geometry of die and plug to reduce the drawing force just using the FEM simulation. The simulation result has been compared with experiment. Zhang at al. [3] investigated surface roughening analysis of cold drawn tube. The micro-scale finite element model with initial surface roughness was used for simulation. Toribio at al. [4] analyzed the influence of hydrogen embrittlement on parameters of the wire drawing process using various FEM numerical simulations.

This paper is focused on the comparison of the result of the strain values obtained by experiment and FEM simulation using software DEFORM 2D and Lagrangian formulation of simulation problem.

2. Experiment

Steel grade E235 and E355 (ferritic-pearlitic carbon steels with the chemical composition given in Table 1) were investigated experimentally; as a feedstock for cold drawing a hot rolled tube with dimensions of Ø70 × 6.3 mm was selected.

Mechanical properties of E235 steel can be summarized as follows: yield stress R_e = (226 ÷ 245) MPa, tensile strength R_m = (343 ÷ 441) MPa and ductility A_5 = 24 %. Mechanical properties of E355 steel are: yield stress R_e = (335 ÷ 355) MPa, tensile strength R_m = (490 ÷ 630) MPa and ductility A_5 = 24 % [6].

Table 1. Chemical composition of E235 and E355 steel grade in wt. % [5].

	C	**Mn**	**Ni**	**Cu**	**Mo**	**Sn**	**P**	**S**	**Si**	**Ti**	**Cr**
E235	0.090	0.420	0.060	0.140	0.020	0.012	0.013	0.011	0.200	0.002	0.060
E355	0.180	1.220	0.110	0.170	0.030	0.017	0.025	0.012	0.270	0.002	0.100

Chemical treatment of the tube (pickling, phosphating, lubricating) was made before cold drawing process. Geometrical and technological parameters for experimental tube drawing are shown in Table 2. Calculation of tube cross-section (area) reduction come given by

$$Reduction = \frac{S_R}{S_0} \cdot 100\ [\%], \quad (1)$$

where the ($S_R = S_0 - S\ [mm^2]$) ,($S_0\ [mm^2]$) is the tube area before drawing and ($S\ [mm^2]$) is tube area after drawing.

In the 1st pass the area reduction was 40.52 %, and in the 2nd pass, the area reduction was 27.34 %. The final reduction of the tube cross section area for two-pass technology (from Ø70 × 6. 3 mm to Ø50 × 3.75 mm) was 57.78 %; the value was divided rather uniformly among all passes (see Table 2).

Table 2. Geometrical and technological parameters for experimental tube drawing.

	Feedstock dimensions [mm]			**Tube dimensions [mm]**			**Pointing [mm]**		**Reduction [%]**		
Pass No.	O.D.	W.T.	L	O.D.	W.T.	L	L (tip)	Ø (tip)	Total	W.T.	O.D.
1	70	6.30	4300	55	4.75	6725	300	40	40.52	25	21
2	55	4.75	6725	50	3.75	9255	300	40	27.34	21	9

O.D.-outer diameter, W.T.-wall thickness, L-length

The local plastic deformation of the tube was analyzed. During subsequent drawing steps, the tube undergoes plastic deformation. Final geometry and properties of deformed tubes depend on strain value. It is possible to investigate the change of material structure and predict plastic deformation.

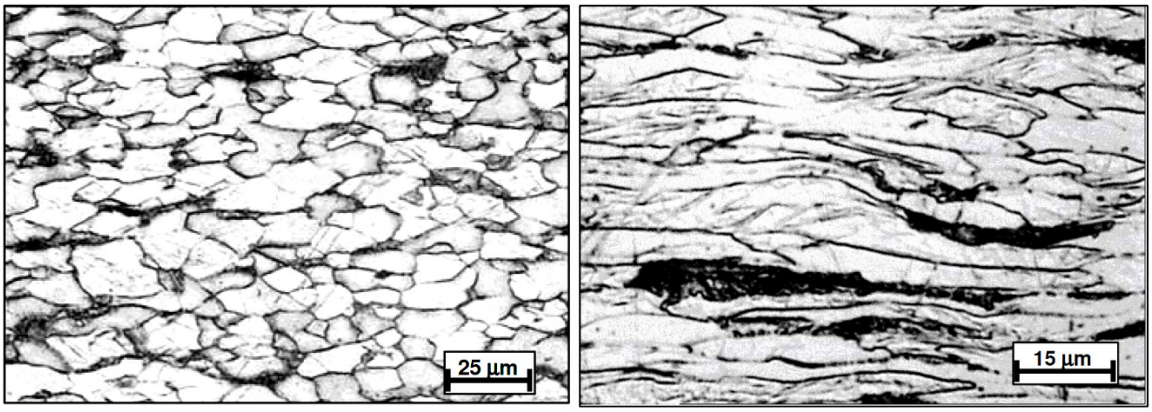

Figure 1. Example of the undeformed microstructure (left), deformation after two pass (right) [5].

The microstructure after both passes was investigated in orthogonal tangential and longitudinal planes of the deformed tube by light microscope (500× magnification) on metallographic cut (Figure 1). Three tangential metallographic cuts were prepared: 1. on the inner surface of the pipe wall "I", 2. on the outer surface of the pipe wall "O" and 3. in the middle of the pipe wall "M" (Figure 2). The structure anisotropy increased due to plastic deformation – grain boundaries orientation in deformed area of the piece was evaluated. The local strain in analyzed area was obtained by stereological measurement of the degree of grain boundaries orientation [7]. The anisotropic microstructure was decomposed into isotropic and planar oriented components using quantitative metallography [8] (Saltykov stereology methods with oriented test lines). Measured and calculated parameters of local plastic deformation in the deformed zone are summarized in Table 4.

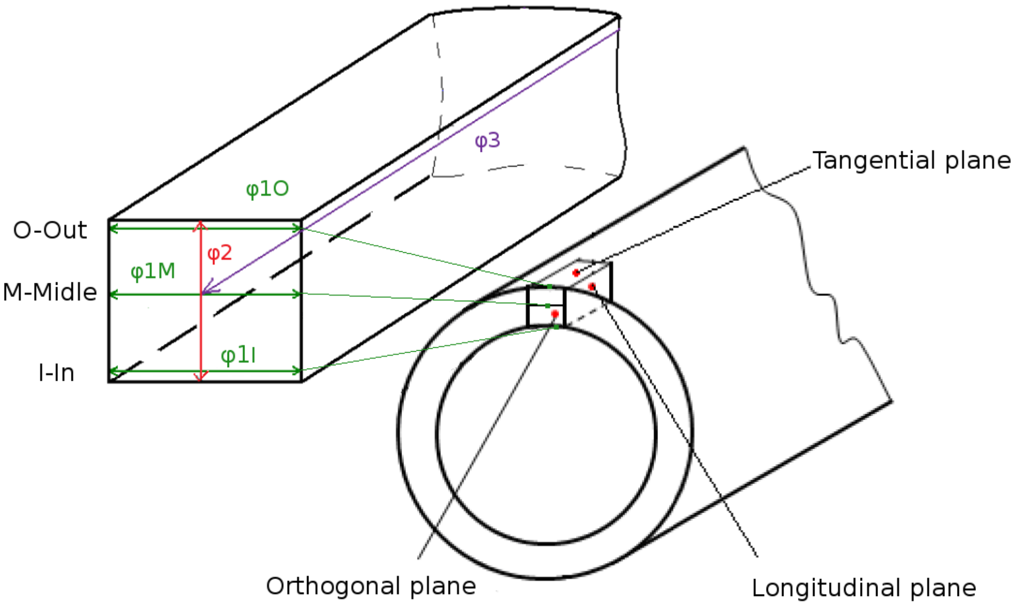

Figure 2. Metallographic cuts and planes on the part of the deformed tube.

3. Numerical simulation

DEFORM 2D and the Lagrangian calculation has been set for numerical simulation of cold drawing technology. The initial axisymmetric geometric configuration has been set. The data interpolation functionality was used to set the second pass calculation. The final data from the first pass was transformed and set the second pass. This data transformation must be realized because drawing technology was performed without interoperative annealing.

3.1. Workpiece and tools of material modelling

As the temperature stays lower in cold drawing, the material properties do not vary and can therefore be supposed to by independent of the temperature variation. As the material behavior is considered temperature independent, the power law constitutive equation of material plastic properties can be used

$$\sigma = c\varepsilon^n \dot{\varepsilon}^m + y \quad (2)$$

where ε represents the equivalent effective plastic strain, $\dot{\varepsilon}$ represent the effective plastic strain rates, and c, n, m, y material parameters are determined by means of tensile tests [5], they are listed in Table 3. The tube material was considered as plastic, the hardening is assumed as isotropic, and yield function type is set as Von Mises. Elastic material properties can be neglected, the workpiece is set as a plastic.

Table 3. Materials parameters of the stainless steels for Eq. 2.

	Parameter	E235 material	E355 material
c	Material constant (-)	178	404
n	Strain exponent (-)	0.61	0.63
m	Strain rate exponent (-)	0.02	0.02
y	Initial yield value (MPa)	235.5	345

3.2. Tools geometry, properties and simulation condition

The drawing velocity was set 9 m.min^{-1} for all passes in experimental drawing and simulation boundary conditions. The forming tools, (mandrel and die) was considered as rigid bodies. Tool dimensions are given in Table 2. The friction model between the tools and the material was chosen to be a shear-type with the value of 0.08. The geometry of the tube has meshed. The eight elements are across the wall of the tube is in the first pass the six are in second pass Figure 4. This mesh of workpiece is sufficient for accuracy and does not need to be re-mesh procedure during the calculation. The mesh of tools did not need to be generated for simulation

4. Result and discussion

Comparison of strain values measured by the stereological method with values obtained from the simulation was possible. The strain in all directions was analysed according to Figure 2. The φ1 strains were examined in three sections of the cross-section of the tube wall (Figure 3). Strain φ1I is near the inner surface, strain φ1O is near the outer surface, and strain φ1M is in the middle of the tube wall. As shown in Figure 3, after the 1st pass the difference of strain between the E235 and E355 is minimal. Smaller negative strain was identified on the inside of the tube ”A” then on the outside of the tube “B”. The same result was obtained after 2nd pass.

Calculated values of radial strain φ2 for all passes and materials can be seen in Table 4. Due to high reduction 40.52 % after the first pass, there is an obvious positive φ2 strain in deformed area. After the second pass, where the reduction area is 27.34 %, there is an only negative φ2 strain. Calculated values of φ3 strain for all passes and materials are shown in Figure 4.

The initial strain of undeformed tube is 0. After the first pass φ3 strain was approximately 0.54 for E235 and also E355 material (Figure 4 left). Data interpolation method was used for initialization of the second pass. Initial strain for the second pass was between 0.550 and 0.625 (Figure 4 right). Mechanical properties from tensile testing and Vickers hardness for both materials are shown in Figure 5.

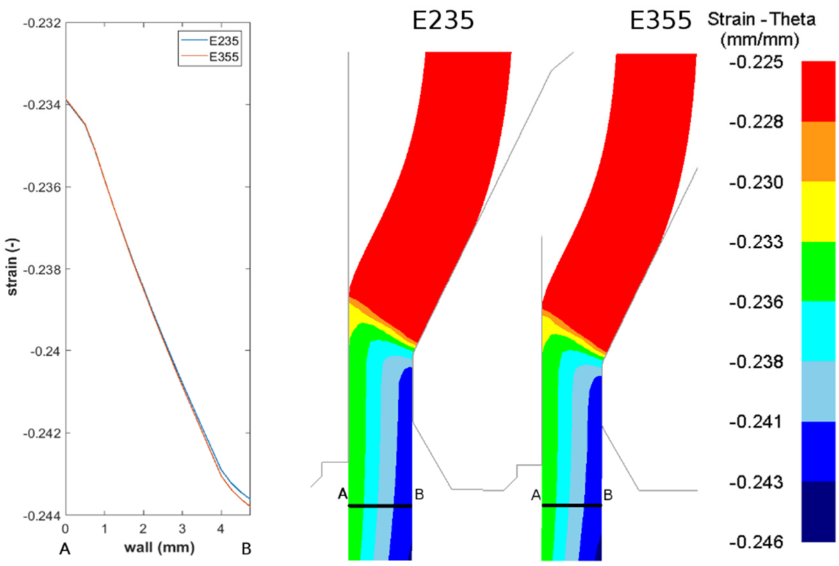

Figure 3. Strain φ1 across the wall of the tube after the 1st pass.

Table 4. Stereology methods and simulation strain values result.

		Values obtained by stereological measurement [5]					Values obtained by numerical simulation				
		φ1O	φ1M	φ1I	φ2	φ3	φ1O	φ1M	φ1I	φ2	φ3
E235	**Pass 1**	–0.241	–0.237	–0.215	–0.282	0.520	–0.243	–0.239	–0.232	–0.298	0.537
	Pass 2	–0.336	–0.320	–0.301	–0.519	0.839	–0.339	–0.324	–0.305	–0.551	0.874
E355	**Pass 1**	–0.241	–0.237	–0.232	–0.282	0.520	–0.243	–0.239	–0.233	–0.297	0.536
	Pass 2	–0.336	–0.320	–0.300	–0.519	0.839	–0.339	–0.324	–0.305	–0.55	0.874

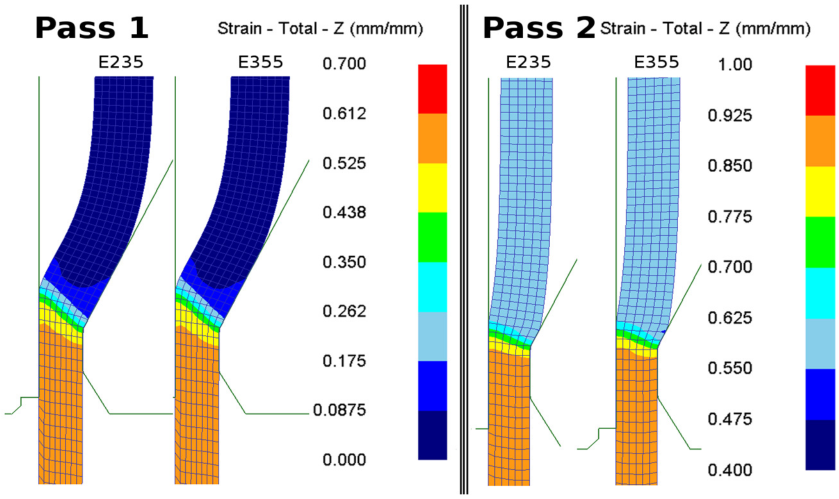

Figure 4. Pass 1 and pass 2 strain φ3 for E235 and E355 steels.

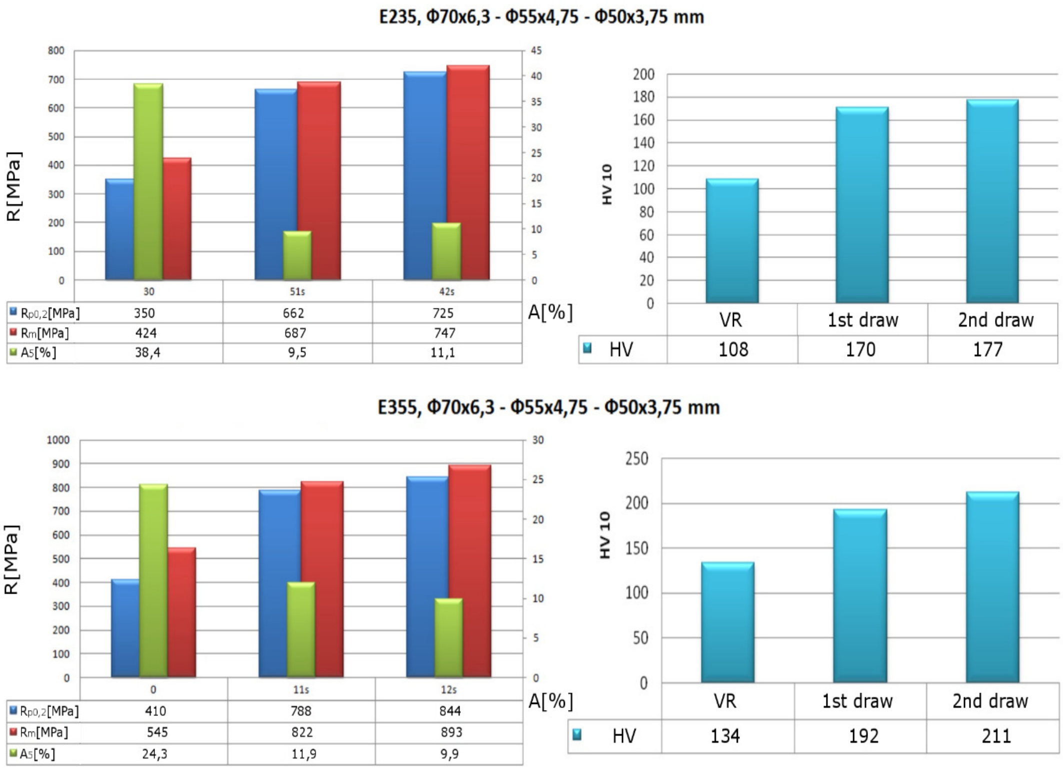

Figure 5. Mechanical properties: tensile testing (left) and Vickers hardness HV (right).

The hardness measured after the second pass was 177.2 HV for E235 material and 211.4 HV for E355 material. Tensile test after the second pass was higher for E355 material (893 MPa) than for E235 steel (747 MPa).

5. Conclusion

The key topic of this paper is to compare parameters of plastic deformation obtained experimentally by measurement of microstructural characteristics of oriented grains with data obtained from FEM simulation using axial-symmetric Lagrangian formulation. Excellent agreement of final strain values from FEM simulation and stereological measurement was achieved. FEM simulation allows analyzing many other parameters of the forming process. Deformation tensor, stress tensor, tool load, tool wear, etc. It is necessary to define correctly the simulation boundary conditions, geometry and material properties for Compliant and Correct Results. Defining tools as rigid and defining a forming material as plastic using Power Law definition appears to be sufficient for simulation of the cold drawing process.

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