

Evolution of deformation texture in cold drawing of steel tubes using EBSD analysis and FEM simulation

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Abstract. Cold drawing of steel tubes is the manufacturing process characterized by anisotropic material flow during drawing. In this paper, the microstructural of the E235 steel tube after recrystallization annealing and cold drawing were characterized by optical microscopy and EBSD (Electron BackScatter Diffraction) analysis performed on a scanning electron microscope. The input feedstock after recrystallization annealing with dimensions of $\varnothing 25.0 \text{ mm} \times 1.5 \text{ mm}$ (O.D $\times$ W.T.) was cold drawn in two drawing passes with fixed plug to the final dimensions of $\varnothing 18.0 \text{ mm} \times 0.9 \text{ mm}$ (O.D $\times$ W.T.). The development of crystallographic texture (both qualitative and quantitative) was analysed on a longitudinal section of the tube. The stress-strain state in the tube material during drawing was calculated by FEM (Finite Element Method) software and the development of the texture depending on the stress-strain state in three different directions using cylindrical coordinates with respect to the drawing direction was evaluated. We have investigated the ratio of individual crystallographic planes depending on stress state during drawn tube. The main objective was to define the development of crystallographic grain orientation from stress- strain state during cold drawn tube.

1. Introduction

Cold tube drawing is a metalworking process used to produce high-quality seamless tubes with precise dimensions, good surface, finish and high mechanical properties. Seamless tubes are used for applications where homogeneity of strength, microstructure, and extended product life are important design parameters. Cold drawing is widely applied in the industrial production of seamless tubes, employed for various mechanical applications. Cold drawing of steel tubes is the manufacturing process characterized by anisotropic material flow during drawing. In order to achieve the final



diameter and wall thickness, the extruded pre-tubes are reduced successively in several cold drawing steps. In the first passes, where the outer diameter and wall thickness is reduced, the drawing with the fixed plug is used. Hollow sinking is a final process in which the wall thickness stays the same and the outer dimension is reduced [1, 2].

The low temperature during the cold drawing process doesn't enable dynamic recrystallization and thus occurs the material hardening due to the accumulation of dislocations. During the forming process, individual grains are elongated in the direction of the main deformation. Too high level of deformation and hardening is connected with a depletion of material plasticity and the risk of defects, and therefore recrystallization annealing is required. During the annealing, the new deformation-free equiaxial grains are formed and the material is capable of being further deformed [2, 3, 4].

The aim of metal forming industry is perpetually improve productivity and product quality. In order to reach this purpose, a better understanding of the processes is necessary. On the one hand, a large series of experimental tests can be done. However, this type of approach may be time and money consuming. On the other hand, lots of tests can be performed virtually thanks to finite element (FE) modelling. It also gives access to physical values, such as stresses and strains, which are not measurable during the process. Thus, FE modelling seems to be a helpful tool [5].

2. Materials and methods

The material used in this study is E235 steel grade with ferrite and pearlite (8.9 %) microstructure. The the volume fraction of the pearlite in steel was determined by calculation based on the carbon content. The chemical composition of the used steels is in Table 1. The samples for metallographic characterization were hot fixed into a polymeric resin and subsequently grinded and polished. Mechanical-chemical polishing using colloidal silica (OP-S Struers) took place as a final step. The input tube with dimensions of $\varnothing 25.0 \text{ mm} \times 1.5 \text{ mm}$ (O.D $\times$ W.T.) was the recrystallizing anneal at temperature $580^\circ\text{C} / 34 \text{ min}$. The input feedstock was cold drawn in two drawing passes with fixed plug to the final dimensions of $\varnothing 18.0 \text{ mm} \times 0.9 \text{ mm}$ at the drawing speed $625 \text{ mm} / \text{s}$. The first drawing passes were dimensional from $\varnothing 25.0 \text{ mm} \times 1.5 \text{ mm}$ to $\varnothing 22.0 \times 1.25 \text{ mm}$ (reduction 26.42 %). The second drawing passes were dimensional from $\varnothing 22.0 \times 1.25 \text{ mm}$ to $\varnothing 18.0 \text{ mm} \times 0.9 \text{ mm}$ (reduction 40.67 %). Reduction of tube cross section at drawing was calculated according to the equation (1):

$$R = \frac{(D_0 - d_0) - (D_1 - d_1)}{(D_0 - d_0)} 100 \quad (1)$$

R – reduction of cross section (%), D_0 – outer diameter of tube before tube deformation (mm), d_0 – inner diameter of tube before tube deformation (mm), D_1 – outer diameter of tube after tube deformation (mm), d_1 – inner diameter of tube after tube deformation (mm). Mechanical properties of the material before and after drawing were measured by a tensile test.

The stress state in the material tube during drawing was calculated by finite element software – DEFORM 3D. With respect to the numerical simulation setting, the input tube was defined by flow stress which were achieved of tensile tests. The main objective was to determine the value of the stress in which the crystal lattice rotation occurs. DEFORM 3D expresses the stress state in a cylindrical coordinate system $[R, \theta, Z]$.

The crystallographic orientation of grains with individual orientations was examined by means of EBSD method. EBSD maps were acquired on an area $\sim 200 \times 150 \mu\text{m}$ using a step size of $1 \mu\text{m}$ and applying a sample tilt angle of 70° at accelerating voltages 20 kV . The obtained EBSD data were processed by HKL Channel 5 software.

Table 1 Chemical composition of E355 steel grade (acc. to STN 411353) in wt. %

Element	C	Ni	Mn	Mo	Cr	Fe
Concentration [wt. %]	≤ 0.09	≤ 0.06	≤ 0.42	≤ 0.02	≤ 0.06	Bal.

3. Result and discussion

EBSID analysis was realized with object to understand the development of crystallographic texture during the drawing of precision tubes. The development of textures is shown using inverse pole figures (IPF) in radial, tangential and axial directions of sample. The intensity of IPF is shown by the mean uniform density (MUD). MUD value above unity indicates that there are more data points of a particular orientation than would be expected from a sample that is totally random.

Figures 1 – 6 show inverse pole figures (IPF) maps of the samples after individual technological steps (initial state; after the 1st and 2nd step of cold drawing).

The input tube has a certain inheritance of the weak deformation texture, Figures 1 – 3 (IPF - on the left). There is a strong dominance of (101) to the axial direction, of (111) to the radial direction, of (001) to tangential direction as a result of the previous deformation. The material was completely recrystallized after the previous deformation.

Tube after recrystallization was draw while the components of the strain tensor in the tube during the drawing process act in mutually perpendicular directions. Considering that at the second drawing passes is a larger reduction than at first drawing passes therefore, at the second drawing passes is a higher strain than at first drawing passes, Table 2.

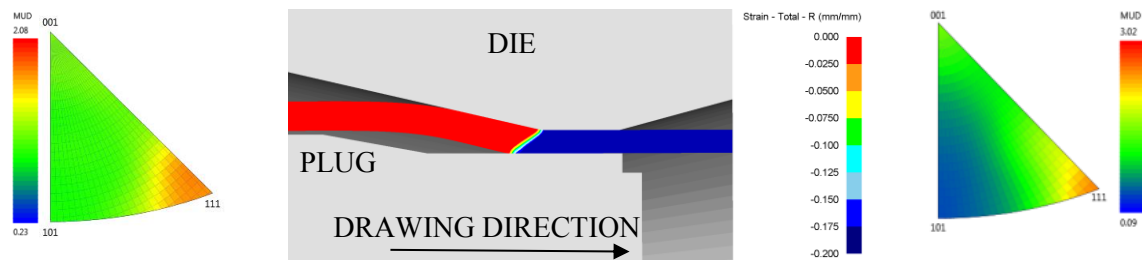


Figure 1 Distribution of strain in the radial direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 1. drawing passes

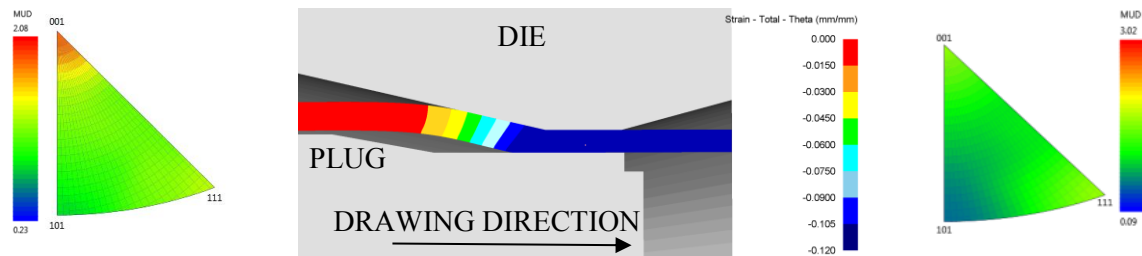


Figure 2 Distribution of strain in the tangential direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 1. drawing passes

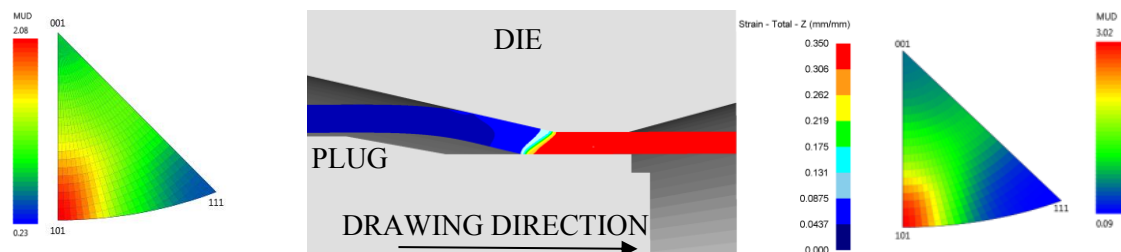


Figure 3 Distribution of strain in the axial direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 1. drawing passes

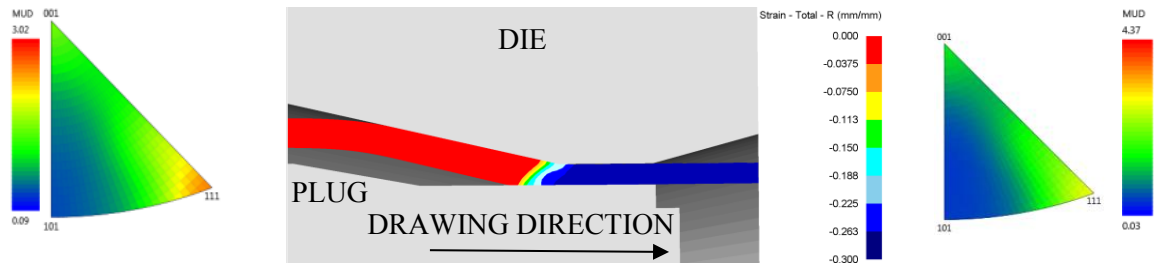


Figure 4 Distribution of strain in the radial direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 2. drawing passes

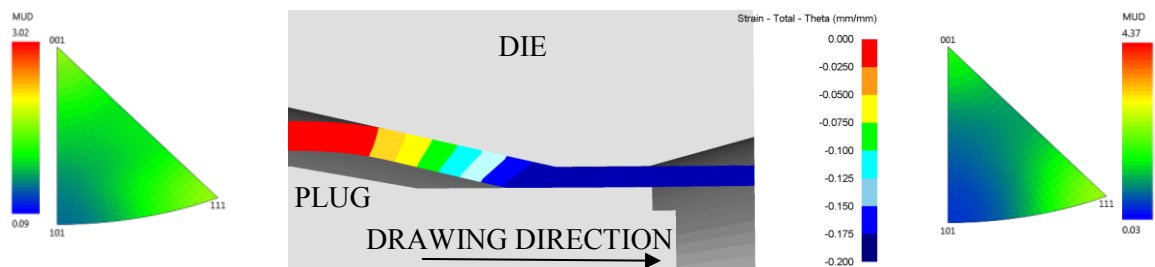


Figure 5 Distribution of strain in the tangential direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 2. drawing passes

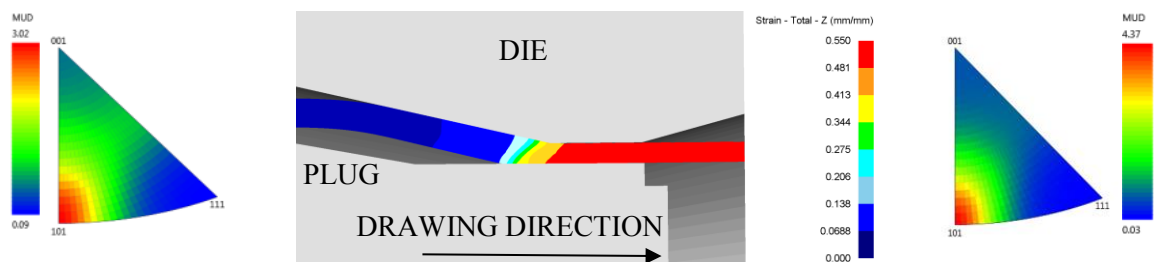


Figure 6 Distribution of strain in the axial direction during drawing (in the middle) and IPF before drawing (on the left) and after drawing (on the right), 2. drawing passes

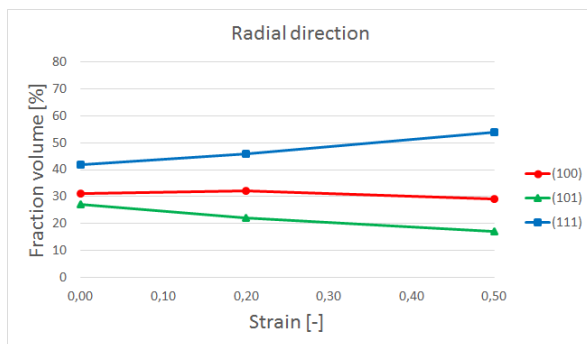


Figure 7 The diagram of the fiber texture evolution during drawing in radial direction

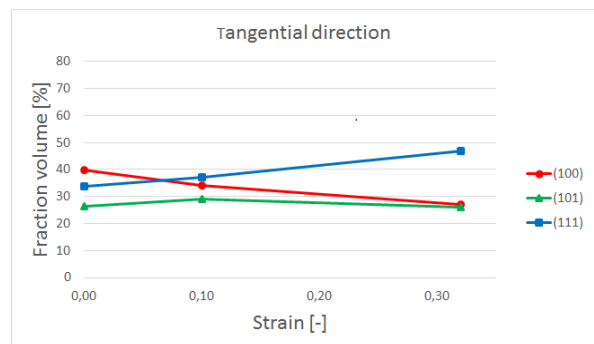


Figure 8 The diagram of the fiber texture evolution during drawing in tangential direction

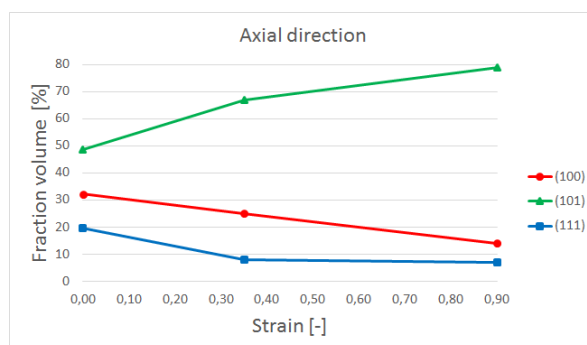


Figure 9 The diagram of the fiber texture evolution during drawing in axial direction

Table 2 Calculated approximate maximum stresses and strains at drawing in the deformation zone by finite element method (FEM)

	Radial direction		Tangential direction		Axial direction	
	1. drawing passes	2. drawing passes	1. drawing passes	2. drawing passes	1. drawing passes	2. drawing passes
Strain [-]	0.2	0.3	0.12	0.2	0.35	0.55
Stress [MPa]	450	675	375	602	351	575

In radial direction was the tube loaded by dominant pressure stress component, as illustrated, Figure 1, Figure 4. The dominant effect of pressure stress caused reduction the wall thickness of the tube after drawing. We can declare, according IPF that pressure stress has influence on increasing of texture (111) from random texture (state after recrystallization). Share of others crystallographic texture (001), (101) have been realigned into texture (111) (Figure 7). The development of the texture is steady from an increasing deformation.

In tangential direction was the tube loaded by dominant pressure stress component, as illustrated Figure 2, Figure 5. The dominant effect of pressure stress caused reduction the outer diameter of the tube after drawing. And also, pressure stress caused increasing density of poles in texture (111). The texture (001) (state after recrystallization) changed significantly and unlike texture (101) which density of poles was reduced (Figure 8). This fact is substantiated of high critical slip stress required to rotate the plane (001) compared to other planes in the BCC (Body-Centered Cubic) grid [6].

In axial direction was the tube loaded by dominant tensile stress component, Figure 3, Figure 6. The tensile stress in the axial direction caused a prolongation of the tube. We can declare, according IPF that pressure stress has influence on increasing of texture (111) from random texture (state after recrystallization). Share of others planes were decreased from dominant tensile strain/stress, Figure 9. The crystal plane (101) in the body-centered cubic (BCC) lattice of ferrite is the most densely occupied by atoms and therefore the deformation occurs by sliding in this plane.

The axial stresses/strains are higher than in radial and tangential direction, it caused that texture development in the axial direction is more distinctive than radial and tangential direction. When the material is stretched the angle between the drawing direction and the slip direction is decrease and when the material is compressed the opposite is occur [7]. For that reason, the pressure stress during drawing increases the Schmid factor. Therefore, higher pressure stress is needed to rotate the crystal in material. The rotation of the crystal was less pronounced in second drawing pass than in first drawing pass, because of deformation hardening during first drawing pass prevented it. Ultimate tensile strength during first drawing passes has increased from $UTS = 388 \text{ MPa}$ to 602 MPa and during second drawing passes has increased from $UTS = 602 \text{ MPa}$ to 710 MPa , (Table 3).

Table 3 Mechanical properties ($R_{p0.2}$ – yield stress, R_m – tensile strength, A_5 – elongation)

State	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Recrystallizing	307	388	46
1. drawing passes	596	602	8
2. drawing passes	685	710	6

Conclusion

The texture characteristic of a E235 steel grade tube is investigated based on electron backscattered diffraction results, this analysis enabled us to reach the following conclusions:

- Crystals in radial and tangential direction rotated by effect pressure the stress into a stable texture (111) that is at pressure stress in BCC grid.
- Crystals in the axial direction rotated by effect tensile stress into a stable texture (101) that is at tensile stress in BCC grid.
- Obtained data served as a valuable basis for the optimization of technological processes of production. The main aim of the study is to obtain the optimal crystallographic orientation of the drawing of seamless steel tube with properties close to deep drawing parameters.

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