Examination of crystal plasticity in cold drawn tube forming using FEM and Voronoi tessellation

M Necpal, M Martinkovič and M Kuruc
Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Ulica Jána Bottu 2781/25, 917 24 Trnava, Slovak Republic

martin.necpal@stuba.sk, maros.martinkovic@stuba.sk, marcel.kuruc@stuba.sk

Abstract. The analyses of the tube drawing process can be divided into two basics parts of investigations - macro-scale and micro-scale. Macro-scale analyses involve investigation of dimensional accuracy of the formed specimen, drawing forces, strain, stress, etc. The analyses of the tube drawing process in the macro-scale have been studied experimentally or theoretically using numerical methods for many years. For the final product of drawing process is also important to know the surface quality for example. For this purpose, it is important to know micro-scale material properties (spatial distribution of grain neighbourhood orientation etc.), and examine the context of micro forming material. There has been a trend in the last decade to make a link between macro-scale forming and micro-scale material properties and name it Multi-scale modelling. This research illustrates the possibility to use Voronoi tessellation grain microstructure model in DEFORM FEM software to predict grain plasticity. The result obtained from numerical simulation is compared with direct reconstruction, derivation of Voronoi tessellation, and measurement using the line and also with analytical theoretical method of strain distribution in tube draw process throw the die.

1. Introduction
The high quality tubes are widely used in various industrial products such as automotive industry pipes for brake liquid, aviation industry coolers, etc. Due to its specially usage, high dimensional accuracy, surface roughness and mechanical properties are required. Cold drawing process is used for manufacturing precision metal tubes and pipes. To avoid material fatigue during draw process it is important to understand material macro formability and also microstructural geometry of material. For this investigation, numerical simulation and computer analyses, usually FEM simulations are widely used.

By macro-scale numerical simulation, it is possible to analyse the material flow. This kind of simulations was applied for a better understanding of the drawing process by Bella [1], Necpal and Martinkovič [2]. Keshavarz [3] in experimental and computational study of Ni-Based superalloy illustrated the need for incorporating the critical microstructural features in plasticity models for understanding the role of microstructure on material behaviour. Zhang [4] investigated the inner surface roughness evolution of the high quality aluminium alloy AA6061 rectangle tube during cold drawing process. The micro-scale analysis with the 3D crystal-plasticity model were conducted based on the macro-scale FEA result. The macro and micro coupling analysis provide a new way to FEM
analysis of the formed part and the plastic deformation of metal material in cold drawing process. This research illustrates FLOWNET functionality in DEFORM 2D software using Voronoi tessellation.

2. Numerical simulation

DEFORM 2D and the Lagrangian calculation has been applied for numerical simulation of cold drawing technology. The initial axisymmetric geometric configuration has been set.

2.1. Workpiece and tools of material modeling

During cold drawing process, the material temperatures remain lower and therefore material behaviour can be considered as temperature independent. In this case, the power law constitutive equation for definition of material plastic properties can be used (Equation 1)

$$\sigma = c \varepsilon^n \dot{\varepsilon}^m + y$$

where $\varepsilon$ represents the equivalent effective plastic strain, $\dot{\varepsilon}$ represents the effective plastic strain rate, and $c$, $n$, $m$ and $y$ are the material parameters determined by means of tensile tests. These parameters are listed in Table 1. The tube material was considered as plastic, the hardening is assumed to be isotropic, and the yield function type is set as von Mises. Elastic material properties can be neglected, the workpiece is set as a plastic.

Table 1. Mechanical properties of the stainless steel materials.

| Symbol | Material parameter | Value |
|--------|--------------------|-------|
| $c$    | Material constant [-] | 178   |
| $n$    | Strain exponent [-]   | 0.61  |
| $m$    | Strain rate exponent [-] | 0.02 |
| $y$    | Initial yield value [MPa] | 235.5 |

2.2. Tools geometry, properties and simulation condition

The drawing velocity was set 9 m.min$^{-1}$ for all passes in experimental drawing and also as simulation boundary conditions. The forming tools (mandrel and die) were considered as rigid bodies. Tool and feedstock 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 [5]. The geometry of the tube was meshed. The eight elements are across the wall thickness of the tube. This mesh of workpiece is sufficient for required accuracy and it is not necessary to use the re-mesh procedure during the calculation. The mesh of tools did not need to be generated for simulation.

Table 2. Tool and feedstock dimensions.

| Symbol | Material parameter | Unit | Value |
|--------|--------------------|------|-------|
| OD     | Outer diameter of the un-deformed tube | mm  | 28    |
| WT     | Wall thickness of the un-deformed tube | mm  | 4     |
| $\alpha$ | Approach die angle | °    | 12    |
| ID     | Inner diameter of the die | mm  | 24    |
| LDS    | Length of the die bearing surface | mm  | 4     |
| ODP    | Outer diameter of the plug | mm  | 18    |
| PT     | Plug and tube contact length “measure after simulation” | mm  | 8.8   |

In Figure 1, the results of 2D FEM simulation in DEFORM software can be seen. Main maximum strain in longitudinal direction through a die is slowly increasing. Rapid increase of strain is in the contact area of drawn pipe with the die, which shown a graphical behaviour of the strain on the internal side of pipe.
3. **Analytical solution**

Calculation of tube cross-section (area) reduction is given by

\[
\text{Reduction} = \frac{S_0 - S}{S_0} \times 100 \quad \text{[\%]}
\]  

where the \( S_0 \) [mm\(^2\)] is the tube cross section area before drawing and \( S \) [mm\(^2\)] is the tube cross section area after drawing. In this example, \( S_0 = 301.59 \text{ mm}^2 \), \( S = 236.40 \text{ mm}^2 \). According to Equation (2), the cross-section reduction is 21.6 %.

![Figure 1. Results of 2D FEM simulation.](image)

Deformation of a workpiece can be quantified by means of its dimensions before and after deformation. Let cylindrical bar has initial length \( l_0 \) and cross-section area \( S_0 \) and is formed by a reduction along its main axis. After deformation its length is \( l \) and cross-section \( S \). The strain is defined as

\[
\varepsilon = \frac{l - l_0}{l_0} \quad [-]
\]  

Forming law of Constant volume means that the volume of material before forming is equal to the volume of material after forming. Volume of drawing tube is defined as

\[
V_0 = V = l_0 S_0 = l S \quad [-]
\]  

Substituting Equation 3 to the Equation 4, it is possible to obtain Equation 5 to define the tension strain, which is primary strain of the tube drawing process.

\[
\varepsilon = \frac{S_0 - S}{S_0} \quad [-]
\]

In this case when the reduction is 21.6 %, the macroscopic tensile strain is \( \varepsilon = 0.276 \).

4. **Investigation of plastic deformation by Voronoi tessellation boundary orientation**

In this case, a combination of FEM simulation and FLOWNET pattern deformation is used to compare true strains. Tensile strain along the axis of the pipe is the main strain with maximum value in drawing process. Maximum main strain obtained by FEM simulation will be compared with strain obtained by boundary deformation degree of Voronoi tessellation.
4.1. Polycrystalline morphology
Mathematically, a Voronoi tessellation of an n-D space is collection of n-D entities that fills the space with no overlaps and no gaps. These entity are polyhedral and are formally defined as zones of influence of particular set of points, corresponding to their centres. Algorithms for the generation of a 2D computational mesh for the Voronoi cell are governed by the principles of Dirichlet tessellation in plane. Subdivision of a planar domain in the tessellation process is determined by a set of points belonging to the domain [6]. Several algorithms have been proposed in the literature to generate Voronoi tessellation or cells in plane. For our purposes, the MATLAB Voronoi standard functions [7] is used to compute the region of Voronoi diagram.

The generation procedure and result of Voronoi cells are illustrated in Figure 2. The first step is generation of random point, they represent the centres of Voronoi tessellation. The size of the region of Voronoi Tessellation is $4 \times 2$ mm, where 4 mm is the thickness of undeformed tube before forming operation.

![Voronoi Tessellation Diagram](image)

Figure 2. The generation procedure and result of Voronoi cells.

4.2. FLOWNET DEFORM functionality
The FLOWNET is a post-processing tool which allows the user to place some 2D pattern into the simulated region and let the simulation track the deformation of the pattern throughout the deformation [8], as shown Figure 3. As the FEM mesh deforms, so does the pattern, however, unlike the FEM mesh, the pattern remains intact also throughout the FEM mesh reconstruction (re-meshing). Thus, the FLOWNET is much like physically etching a pattern on a cross-section of the deformed workpiece. This is an excellent way in which to visualize any potential irregularities in the grain structure or to view potential surface defects such as folds. It should be noted that FLOWNET patterns can be generated for deforming objects. The start step list will contain all of the steps in the display window currently loaded by default.

Voronoi tessellation diagram generated by MATLAB has to be transformed as a user defined pattern file readable by DEFORM software. A pattern file consist of a list of point coordinates and a list of connectivity sets. The points are points of intersection within the FLOWNET.
The strain in analysed area was obtained by measurement of degree of Voronoi tessellation boundaries orientation. On Voronoi tessellation area the test line were placed perpendicular and parallel to the boundaries orientation. From the specific number of parallel test lines intersections with tessellation boundaries ($P_L$)$_p$ and perpendicular lines ones ($P_L$)$_o$, the total specific surface area ($S_V$)$_{TOT}$ of cells and the planar orientation part of specific surface ($S_V$)$_{OR}$ of cells were estimated. From this values, the degree of orientation of cells boundaries $O$ was estimated as ratio of ($S_V$)$_{OR}$ and ($S_V$)$_{TOT}$.

The result is proportional to Voronoi tessellation boundaries deformation degree and local plastic deformation, was estimated according to Equation 6 [9], where $\varepsilon$ is the logarithmic strain.

$$
\varepsilon = \ln \left( \frac{1 + O\sqrt{2 - O^2}}{1 - O^2} \right)^{2/3} \quad [-]
$$

Local plastic deformation, degree of orientation and estimated deformation according to Equation 6 in the zone of Voronoi tessellation pattern before and after the drawing process can be seen in Figure 4.
5. Conclusion

The FEM simulation of the deformation process of the formed material shows complex view of all parameters, not just strain, but also stresses or thermal influences, if they are included in the simulation. For confirmation of the correctness of the simulation model, it is generally required to check at least a part of the obtained results by different method. Analytical method is based on generally valid theoretical influences, it does not give exact information about specific material behaviour.

The use of the quantitative analysis of grain boundary orientation is giving exact view to material behaviour during its deformation. This work shows comparison of FEM analysis and the grain deformation simulation, which is represented as Voronoi tessellation. Qualitative analysis does not provide data in the specific point of material but within a certain volume. The results of individual analyses show that quantitative method of grain boundaries orientation can be used as supplement of computer simulation for confirmation of correctness of simulation model set up.

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References

[1] Bella P, Ridzon M, Mojzis M and Parilak L 2017 The technology of cold drawing of seamless steel tubes using numerical simulation Hutni-Wiadomości Hutnicze 84-8 356–58
[2] Necpal M and Martinkovič M 2019 Evaluation of material deformation during process of precise carbon steel tube cold draw forming IOP Conf. Ser.: Mater. Sci. Eng. 465 012007
[3] Keshavarz S and Ghosh S 2013 Multi-Scale Crystal Plasticity Finite Element Model Approach to Modeling Nickel-Based Superalloys. Acta Mater. 61 17 6549–61 https://doi.org/10.1016/j.actamat.2013.07.038
[4] Zhang L, Xu W, Long J and Lei Z 2015 Surface Roughening Analysis of Cold Drawn Tube Based on Macro–Micro Coupling Finite Element Method J. Mater. Process. Technol. 224 189-99 https://doi.org/10.1016/j.jmatprotec.2015.05.009
[5] Necpal M, Martinkovič M and Václav Š 2018 Determination of the Coefficient of Friction Under Cold Tube Drawing Using FEM Simulation and Drawing Force Measurement Research Papers: Faculty of Materials Science and Technology, Slovak University of Technology 26 (42) 29-34 https://doi.org/10.2478/rput-2018-0003
[6] Ghosh S 2018 Micromechanical Analysis and Multi-Scale Modelling Using the Voronoi Cell Finite Element Method (Boca Raton: CRC Press) https://doi.org/10.1201/b10903
[7] MATLAB https://www.mathworks.com/help/matlab/voronoi-diagram.html?s_tid=CRUX_lftnav
[8] DEFORM™ v11.01 2014 Documentation, Scientific Forming Technology Corporation
[9] Martinkovič M and Václav Š 2013 Estimation of grain deformation of polycrystalline materials Adv. Sci. Eng. Med. 5 585-8