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Precision tube production: Influencing the eccentricity and residual stresses by tilting and shifting

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ABSTRACT

Tube drawing is considered to be one of the most effective and flexible methods to reduce easily tube dimensions, to improve the surface finish, and to design mechanical properties. However, during the production of pre-tubes, it is common to obtain a tube which could still remain eccentric despite being reduced during the drawing processes. This eccentricity causes an increase in weight since dimensioning has to be based on the weakest location of the tube. Moreover, high values of residual stresses can exist after the drawing process, which – in the case of tensile stresses – can promote failure of the tube subject to tension loading. In this paper, the effects of tilting the die and shifting the tube on the eccentricity and the residual stresses were experimentally and numerically determined using as-received tubes and after their subsequent processing. The relative eccentricity change was measured for each tilting angle and shifting value. It has been shown that when a tilted die is used, the final eccentricity varies depending on the tilting angle. For example, using an angle of 5° resulted in a decrease of about 40% compared to the standard condition. By increasing the tilting angle, the surface and sub-surface residual stresses can be decreased. A 3D model using ABAQUS software was developed and verified to describe the evolution of residual stresses and eccentricities.

1. Introduction

Cold drawing is one of the oldest metal forming operations for reducing a cross-sectional area and/or the shape of a rod, bar, tube or wire by pulling it through a die. This process results in excellent surface finishes, closely controlled dimensions, and the desired mechanical properties (Davis and Semiatin, 1989). The deformation is accomplished by a combination of tensile and compressive stresses that are created by the pulling force applied at the exit of die and its configuration (Dieter et al., 2003). Due to vibrations of the mandrel, tolerances in positioning of the die and the billet, as well as potential temperature differences within the billet, variations of thickness can occur along the tube's length and around its circumference causing eccentricity and ovality (Pirling et al., 2008). Eccentricity in the pre-tube influences the circumferential material flow during cold drawing and generates a complex residual stress (RS) pattern, which can affect the mechanical and fatigue behavior of the final tube (Carradò et al., 2013). Moreover, these differences in thickness lead to an (undesirable) increase in the tube volume and weight, which is of special interest for high cost materials. For these reasons, the reduction of tube eccentricity is of importance for the industry, especially for high-precision tubes.

Eccentricity (E) is defined as the percentage of the maximum variation in tube wall thickness from an average value within the same tube's cross section, as described by Eq. (1).

$$E = \frac{t_{\max} - t_{\min}}{t_{\max} + t_{\min}} \tag{1}$$

where $t_{\max}$ and $t_{\min}$ are the maximum and minimum wall thicknesses, respectively. Current industrial copper tube eccentricity is approximately 1–5% (Pari, 2012), while for steel tubes, the eccentricity typically ranges from 2 to 5%, and it is about 3% for aluminum grades (Pirling et al., 2008).

Moore and Wallace (1961) studied the tube sinking through a conical die numerically using the approximation theory. The study was made assuming ideal-plastic behavior and using a smooth conical die. They used an average radius for the analyzed tubes. The Coulomb friction rule and strain hardening were included in the analyses of stresses and strains and the drawing loads and thickness changes were determined (Moore and Wallace, 1961).

The tube drawing process (hollow sinking and drawing with a fixed plug) was modeled by Palengat et al. (2007) using the finite

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element (FE) method. They developed an FE model using ABAQUS software and compared their results with experimental data, focusing on the drawing forces. However, it should be mentioned that they developed a 2D model assuming a tube without eccentricity, so using the axial-symmetrical condition (Palengat et al., 2007).

Residual stresses (RS) can be defined as stresses remaining in a material or body after processing, in the absence of external forces or thermal gradients. They influence the properties of the component and its lifetime. Moreover, RS can play an important role in crack formation and corrosion. RS develop during most manufacturing processes involving material deformations, heat treatment, machining or processing operations, which transform the shape or change properties of material. Kandil et al. (2004) intensively reviewed different methods for measuring RS, and introduced the most common methods for RS measurement, such as hole drilling, X-ray diffraction, synchrotron, etc. Macherauch (1984) also introduced some RS measurement techniques.

In general, RS can be divided into mechanical, thermal, and chemical categories based on its origin. In some operations like rod or bar drawing, welding, machining and grinding, undesirable RS may develop (Xin et al., 2004). Combined with external stresses, RS can be beneficial or disadvantageous for the components. The presence of RS can influence reaction of the material to externally applied stresses. Compressive RS can increase the yield stress and can be used for activities such as strengthening gun barrels and pressure vessels. A compressive stress is considered desirable since it closes surface cracks and allows higher tensile stresses to be generated and improves fatigue properties. However, excessive compressive stresses can cause cohesive and adhesive failures in the case of a coating.

Genzel et al. (1996) studied RS in steel parts produced by cold extrusion and tube drawing. They used neutron diffraction to analyze volume stresses in the extruded rods. In the case of cold drawn tubes, stress evaluation was performed using X-ray diffraction in the axial and tangential directions (Genzel et al., 1996). Pirling et al. (2011) studied the distribution of RS in seamless copper tubes. The experiments were performed on strain imager for engineering applications, SALSA, at the Institute Laue-Langevin (Grenoble, France). Tri-axial residual strain measurements were performed using the high resolution configuration of SALSA with three collimators. An FE model was developed and validated with the experimental results (Pirling et al., 2011).

In recent years, rapid development of computer techniques and application of the theory of plasticity made it possible to apply a more complex approach to the problems of metal-formability and metal-plasticity. Numerical simulation is a very useful approach to optimize designs of tools. The advantage of FE analysis is its ability to model complex forming processes. The effect of each process variable and their coupling effects can be investigated. The results can be used to describe the forming process in a proper way. However, the disadvantage of FE analysis is the complexity in preparing the input data, selecting proper output variables, and interpreting the analysis results (Cho et al., 2006). Concerning tubes, Tekkaya et al. (1985) studied RS in some manufacturing processes such as rod and tube extrusion using FEM. They also performed experimental studies and compared simulation and experimental results and achieved a good agreement (Tekkaya et al., 1985). Tekkaya and Martins (2009) provided an exhaustive basic overview of finite element methods in metal forming processes, focusing on the users, not familiar with the theoretical and numerical procedures behind FEM. Though there is no model suitable for the problem discussed, they introduced different modeling packages and possible sources of errors, worth of interest (Tekkaya and Martins, 2009). Neves et al. (2005) studied their drawing with a fixed plug using FEM and the commercial software MSC Superform to find the best die and plug geometry aimed at the reduction of the drawing force. The numerical analysis helped determine the reactions of the die and plug, the stresses in the tube, the drawing force and the final dimensions of the product. The results of FE model were compared with the results from analytical models and used to design the tools. Different lubricants and different drawing speeds to optimize the drawing force were analyzed (Neves et al., 2005). Mulot et al. (1996) numerically studied the cold pilgering process using 3D FEM. The main purpose of their work was to test a hypothesis and the results of the simplified model, which is used routinely. Their study demonstrated the feasibility of FEM analysis for tube pilgering. They showed that a number of variables and phenomena can be examined numerically. Some are in agreement, qualitatively or even quantitatively, with known values or tendencies, while others still need to be checked experimentally (Mulot et al., 1996). Sawamiphakdi et al. (1991) developed a pre- and post-processing program considering some tube drawing processing parameters to calculate the dimensions, mechanical properties and required drawing forces. The pre-processing program generates FE mesh for ABAQUS program and the post-processing program calculates the aforementioned drawn tube information from the analysis results. They also tried to calculate the RS in drawn tubes (Sawamiphakdi et al., 1991).

In order to be able to control both the eccentricity (decrease or even increase) and RS, tilting and shifting of tubes have been used in our investigation. A 3D model using ABAQUS software (Pawtucket, 2013) was developed and verified to describe the evolution of RS and eccentricities. Both the variation of eccentricity and RS of the as-received copper tubes were investigated depending on the drawing process using different tilting angles and shifting values. Eccentricity and RS of the tubes were measured and compared to the values of the as-received tubes. Finally the results of the numerical simulations were compared to those determined experimentally.

2. Experiments

Annealed SF copper tubes of sizes 65.0 mm × 5.5 mm and 64.0 mm × 3.1 mm (outer diameter × wall thickness) were used. Their chemical composition is given in Table 1. For drawing the tubes, a clamping tool was used. The drawing steps and the parameters of the main die are given in Table 2. The Q-value is defined as the ratio between the deformation in wall thickness ε_s and diameter ε_d ($Q = \varepsilon_s/\varepsilon_d$).

In order to calculate eccentricity, the wall thicknesses of the as-received tubes were measured along their length and circumferentially using an ultrasonic device (Krautkramer CL 400). RS was investigated using the hole drilling method (Stresstech Prism). Steinzig and Ponslet (2003) reviewed thoroughly RS measurement using the hole drilling method and laser speckle interferometry. They described the use of an electronic speckle pattern interferometer and its use in measuring deformations. The processing of image data to obtain deformation data from the area around a drilled hole has been described mathematically (Steinzig and Ponslet, 2003b). They also introduced a technique for extracting RS out of the optical deformation data. They used a full-field least squares analysis for reducing the deformation data to RS results (Ponslet and Steinzig, 2003b). The depth and diameter of the drilled hole were inputs for the calculation of the stresses, and the ability to control these parameters affected the overall accuracy of the technique, as described earlier (Ponslet and Steinzig, 2003a). The RS measurements showed that a good accuracy is possible with this technique, allowing studies to be done where significant amounts of data need to be acquired, giving statistical basis to the results (Steinzig and Ponslet, 2003a).