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Residual stresses evolution in Cu tubes, cold drawn with tilted dies – Neutron diffraction measurements and finite element simulation

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ABSTRACT

The use of cold drawing processes for tubes is a flexible and well-established technology to reduce tube dimensions and improve their surface quality. However, wall thickness deviations over the circumference in the semi-finished goods – eccentricity – and residual stresses can be disadvantageous. Nevertheless, drawing with die tilting is clearly affecting the eccentricity as well as the residual stress development. In this paper the evolution of residual stresses over the wall thickness in cold drawn copper tubes was measured from the as-received state over the condition in the deformation zone with tilted dies and finally to the drawn tubes by means of neutron diffraction analysis at SALSA facility in Institut Laue-Langevin (ILL), Grenoble. A model was developed and the behavior of the residual stresses was simulated using the finite element method (FEM). The information about the evolution was necessary for the model and its verification. With this model – which is taking into account the influence of eccentricity on the residual stress development – the cost intensive neutron diffraction measurements can be reduced strongly. The verified model was used to calculate the residual stresses for standard drawn tubes and compared to tilted ones.

1. Introduction

1.1. Tube drawing

Cold formed semi-finished products face an increasing demand from industry as being producible to dimensional precision and high surface quality. The final products, on the other hand, may have inhomogeneous distributions of their mechanical properties and residual stresses (RS) arising from the elastic response of the material because of an inhomogeneous distribution of elastic–plastic strains. These material properties may cause distortion in further manufacturing operations and, consequently, precision of components then could be reestablished at higher costs only [1]. In order to improve the surface finish and obtain requested mechanical properties in tubes, tube drawing is one of the most effective and flexible methods to shape a tube and reduce the tube's dimension. However, many parameters affect this process - positively or negatively – such as tools' geometry, friction, drawing force, the amount of thickness reduction, etc. [2]. Since the deformation is accomplished by a combination of tensile and compressive stresses - created by the pulling force applied at the exit of the die and its configuration [3] - the drawn tubes have significant tensile RS, often being a negative point for their final use. Moreover, due to vibrations of the mandrel, tolerances in positioning of the die and billet as well as potential temperature differences within the billet, variations of thickness over length and circumference can occur, causing eccentricity (the maximum variation in tube wall thickness from an average value within the same tube's cross section) and ovality [4]. In order to overcome this point, Foadian et al. [5] developed a method to influence the eccentricity in tubes by tilting the die in the drawing process or shifting a pair of dies one against the other to control the material flow during the process and to control the wall thickness variations. Fig. 1 presents a sketch for tilting where a die holder was used to tilt the main die, used for reducing the tubes' diameters (Fig. 1-a). Depending on the position of the max/min wall thickness in the tube, the setup of the dies must be adapted, as it is possible to reduce as well as increase eccentricity. Therefore, a positive and negative setup were defined: when the maximum wall thickness is in the direction of the tilting it is called "positive setup" and vice versa. In case of a negative setup, eccentricity decreased, in case of a positive setup, eccentricity increased. This could be interesting for applications where there is the need of locally increasing or decreasing the thickness of the wall. Concerning RS, the results achieved using the hole drilling method are presented. These results are limited to the near outer surface area (ca. 0.5 mm) of the tube. A complete RS profile through the wall thickness is not presented in this work, but detailed information can be found in [5–7].

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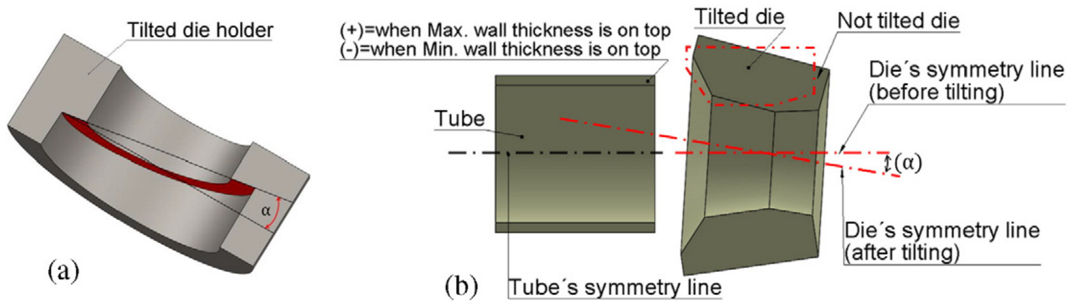

Fig. 1. (a) Die holder used for tilting the main die, (b) definition of a positive and negative tilting setup [7].

1.2. Residual stresses

Residual stresses (RS) act in a body without external forces or moments. The internal forces form a system of equilibrium. If parts of the body are removed, for instance by machining, the state of equilibrium is generally disturbed, and the body reacts by deformation. RS developed during tube drawing influence the mechanical behavior and durability of tubes used for pre-stressed concrete structures, particularly the shape of the stress–strain curve, stress relaxation losses, fatigue life, and environmental cracking susceptibility [8].

Residual stresses have their origin in thermal, mechanical, and/or chemical (metallurgical) changes/behavior. In case of cold drawing, the development of RS mostly is based on the mechanical process. In operations like tube drawing, welding, machining and grinding, undesirable RS may develop. Cold-forming generates RS arising from the elastic response to inhomogeneous distribution of plastic deformation [9]. Depending on how RS interact with external loads, they can influence the mechanical behavior and lifetime of components in a positive or negative way. Advantageously, surface compressive RS can hinder the initiation of fatigue cracks. Disadvantageous effects of RS in metals include highly varying stress gradients (e.g. in the vicinity of welded joints) and reduced dimensional accuracy of a component due to distortion. RS can reach the magnitude of the yield limit and can cause plastic deformation. Therefore, the control and minimization of RS through the production process is an important technological challenge. It is often unmanageable to eliminate RS by using a post-heat-treatment because it is too expensive and could modify the designed microstructure and mechanical properties of the component [10].

Various techniques for evaluating RS, such as X-ray, X-ray synchrotron radiation and neutron diffraction non-destructive techniques, nano-indentation [11] and destructive sectioning method [12] have been developed. Non-destructive measurements of the internal strain field, within the bulk of a copper tube is a challenge to engineers, metallurgists and experimental physicists since many years [13]. Neutron diffraction is a powerful tool for the non-destructive testing of RS in bulk products and advanced materials (metals, alloys, or composites). Its uniqueness is largely due to its most important features, that is, non-destructive testing, the large depth of the penetration of neutrons in a material, and the ability to determine the atomic structure, phase composition, preferred grain orientation (crystallographic texture), RS, and mechanical features of the microstructure (micro-strain and shape and size of coherently scattering crystallites) [14].

1.3. Finite element method

In recent years, rapid development of computer techniques and the application of the theory of plasticity made possible to apply a more complex approach to problems of metals formability and plasticity [15]. 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 and the results used to design the proper forming process. The disadvantage of the FE analysis is the complexity in preparing input data, selecting proper output variables, and interpreting analysis results [16]. Works carried out in the last years in the field of measurement and simulation of RS in cold drawn products have shown that it is possible to obtain reliable quantitative RS values and, in addition to this, to compute numerically RS by modeling the cold-drawing process [9].

Kriska et al. [17] studied the evolution of RS (ex/in-situ) in a pearlitic steel in a cold drawing process using neutron and X-ray diffraction methods. They also studied RS in axial and transverse directions. XRD results indicated that the total RS evolution during severe cold drawing can be described in terms of two distinct regimes: low and high deformation regimes. Moreover, ex-situ neutron diffraction pointed out a strong orientation dependence of the lattice spacing evolution beyond a true strain of ≥1.2. Finally, in situ neutron diffraction had – in contrast to some results reported earlier in literature – revealed strong differences in yielding and stress partitioning among particular {hkl} reflections [18]. Rocha et al. [19] studied axial RS in AISI 1045 steel in a combined cold drawing chain using hole drilling and X-ray methods. They varied the cold drawing parameters to evaluate their influence on the RS distributions. They stated that the RS characteristic, produced in pre-process steps, could be found even after the last manufacturing steps. He et al. [20] simulated RS in cold drawn steel wires using the FE method. They developed an isotropic 2D and 3D FE model and compared the results with the measured results from X-ray diffraction method. A good agreement between the calculated axial RS, based on an anisotropic model, and the measured result by means of X-ray diffraction was stated. The study of RS in cold drawing and their effect on the properties of the materials was not done only in crystalline

Table 1
Chemical analysis of the SF-Cu tube.

wt.%	Zn	Fe	Si	Mg	Te	As	Sb	Al	C	Cu
SF-Cu	0.047	0.018	0.017	0.012	0.018	0.0019	0.012	0.013	0.0063	Balance