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A miniature physical simulator for pilgering

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ABSTRACT

Pilgering is a complex incremental manufacturing process for seamless tubes. In this work, a miniature physical simulator for pilgering was designed and fabricated. This miniature simulator employs a grooved roll-die and a mandrel and can impose controlled reductions in both tube diameter and wall thickness. Pilgering deformation over a range of ratios of reductions in wall thickness and in tube diameter, known as the Q-factor, was imposed on hemi-cylindrical zirconium alloy specimens. The influence of the Q-factor on the microstructure and deformation texture of the deformed specimens was quantified. A polycrystal plasticity calculation based on the binary tree model was used to simulate texture evolution during the simulated pilgering process. The computer model quantitatively captured the variation with Q of the Kearns factors, as measured in the physically simulated specimen. The small differences noticed between the predicted and experimental final textures point to unaccounted transverse components of the flow field. These observations suggest that physical and/or computer simulations can form the basis of a rapid methodology for tool selection to realize prescribed post-pilgering textures.

1. Introduction

1.1. Tube forming by pilgering

Pilgering is an incremental compression forming process, which involves repeated rolling of a tubular job over a mandrel using a roll-die with a tapered groove (Fig. 1(a)). Combinations of forward and return strokes plus appropriate rotations about the tube axis ensure manufacturing with precise dimensional tolerances. As described in detail by Verlinden et al. (2007), the pilgering process involves 'biting' followed by forging, polishing and then idling in a single pilgering stroke. The tapered groove on the roll-die allows variation of the imposed deformation with axial position during a stroke. Cold pilgering yields very high reductions even in difficult to form materials. The nuclear industry has used pilgering for the fabrication of seamless zirconium (Zr) tubes. Processing routes involving alternating pilgering and heat-treatment steps, to produce thin walled tubes for fuel clads, have been described by Saibaba (2008). This work emphasizes the determination of a processing route to fabricate a tube product that meets service requirements; the relationship between processing route and tube properties was not systematically studied.

The roll-die/mandrel tooling lies at the core of pilgering technology, as it determines the productivity and dimensional control over the processed tube. The effect of the tooling geometry on important macroscopic properties such as surface roughness, propensity for oxidation, and formability, has been investigated in the literature. For example, Aubin et al. (1994) correlated the incidence of surface defects to tool design and rolling parameters. Abe and Furugen (2012) made an important contribution to formability assessment during pilgering. They related the critical strain to inner wall fissuring during pilgering to the strain at failure developed in an equivalent compression specimen aligned with the circumferential direction. These process-property relationship characterizations were limited to the macroscopic scale, and did not provide a microstructural explanation. The relationship between the surface roughness and oxidation rate of the tube surface was investigated by Akhiani and Szpunar (2013). In addition to obtaining macroscopic characterizations, these authors also established a microstructural relation between the orientation of the monoclinic oxide grains, and the h.c.p. Zr.

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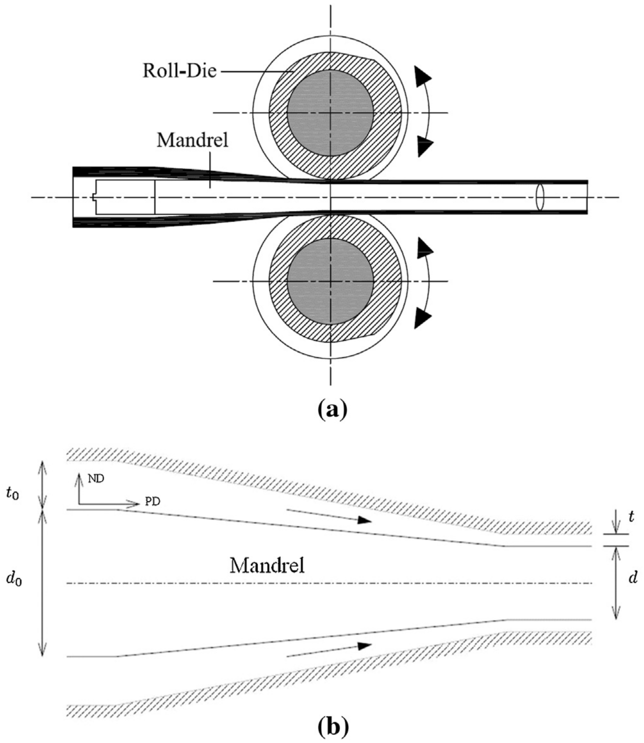

Fig. 1. Schematic of the (a) pilgering process and (b) flow through a convergent channel. (a) Highlights the grooved roll-die and the mandrel: tools important for the physical simulator. The idealized flow shown in (b) was used in an earlier study by Gurao et al. (2014) and Singh et al. (2015a), and is used in the present manuscript, for modeling the texture developments during pilgering. In (b), the pilgering (PD) and normal (ND) directions are shown. Also indicated are the initial and final tube diameters (d_0 and d) and wall thicknesses (t_0 and t).

1.2. Crystallographic texture

An important characteristic of a pilgered Zr tube, which determines its suitability for nuclear applications is its crystallographic texture. Again, the development of the crystallographic texture is determined by the tooling. The crystallographic texture affects in-service behavior such as creep-rate and irradiation swelling, as summarized in the review by Tenckhoff (1988). The crystallographic texture also determines the orientation of hydride precipitates, which are potential locations of brittle crack initiation. The crystallographic texture, and hydride precipitate orientation were correlated by Shinohara et al. (2009) and Vaibhaw et al. (2008). The latter authors also established a correlation with in-reactor performance of the pilgered tubes. Internal stresses developed in the pilgered tube and the crystallographic texture were related by Gurao et al. (2014). In summary, a strong correlation between both microscopic and macroscopic tube properties and crystallographic texture has been established by these works. This suggests that process design to enhance material properties of the tube product will require a good understanding of the relationship between tooling, and the final crystallographic texture.

Producing a number of geometric variants of the tooling in order to establish the relationship between tool geometry on the one hand, and material flow, and crystallographic texture development, on the other, is not usually feasible in a full-scale pilgering mill, due to material, time and cost constraints. Therefore, attempts have been made to understand texture development through polycrystal plasticity simulations. Lebensohn et al. (1996) and Girard et al. (2001) used the viscoplastic self-consistent (VPSC) polycrystal plasticity model to predict the final texture after pilgering. They could obtain qualitative comparisons between computer simulated and experimental textures after multiple pilgering passes. More recently, some of the present authors (Singh et al., 2015a) used a binary tree based polycrystal model to predict texture evolution during pilgering. They too obtained only qualitative agreement with textures measured in a partially pilgered tube.

A commonality between these modeling works is the deformation history imposed: all works assume that the material flow during pilgering is akin to monotonic flow through a convergent channel. In Girard et al. (2001), and Singh et al. (2015a), an additional uniform shear component, representing frictional interactions between tube and tooling was superposed over the monotonic flow. The assumed deformation history in the computer simulations is in stark contrast with the full-scale process, wherein non-monotonic time-varying normal and frictional contact forces are applied.

The reason for the quantitative deviation between the texture measured in a pilgered tube and that predicted by computer simulations is not presently clear. These deviations may arise from inaccurate caputing of the processing conditions. More specifically, the deformation history imposed in the computer simulations may be unrealistically idealized. Alternately, inaccuracies in capturing the material deformation may underlie the deviations. Thus, the computer simulations may be missing important slip and/or twinning modes activated in the physical material, which help accommodate the imposed plastic deformation.

1.3. Physical simulation of pilgering

Physical simulations of properties and microstructures are an important aspect of complex forming and thermomechanical processing. For example, deformation simulators have been successfully used to optimize roll-pass schedules by Abe et al. (2000). As another example, the bulge test for laboratory forming limit diagrams provides important inputs to more complex sheet metal forming, as in Hwang et al. (2009). This context naturally suggests a miniature physical simulator for pilgering. Such a physical simulator will enable the examination of many more tool geometry variants than would be possible in a full-scale pilgering mill, on account of the much lower associated material, time and cost requirements. The physical simulator also permits more control over the imposed tube deformation than a full-scale mill. The present authors are unaware of any studies of pilgering based on physical simulation, reported in the literature.

In this study, a physical simulator for pilgering capable of imposing controlled monotonic deformations is designed, fabricated and used to study the variation of final microstructure and texture with tooling geometry. The tooling geometry is parameterized by a standard scalar process variable namely, the Q-factor, due to Abe et al. (1994). The monotonic loading pattern of the simulated pilgering process is compared with the texture predictions obtained from a binary-tree based polycrystal plasticity model, proposed by Mahesh (2009).

During physical simulations, controlled monotonic deformation is applied to the specimen. Differences between the deformation path imposed in the physical and computer simulations are thus minimized. A key finding of the present study is that the crystallographic texture after physically simulated pilgering agrees quantitatively with that obtained from computer simulations. This suggests that the micro-mechanisms of plastic deformation are accurately captured in the present computer simulations. Assuming that micro-mechanisms accommodating plastic deformation must remain the same in both physical and full-scale pilgering, the present observation suggests that mismatches between computer predicted and measured textures must be exclusively attributed to differences in the deformation path. This, in turn, means that improving the accuracy of the imposed deformation history in