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Anisotropic mechanical behavior and formability criterion for zinc sheets

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ABSTRACT

The mechanical behavior of zinc has been studied and linked to the formability of sheets. An anisotropic elastic–viscoplastic behavior law has been developed to take into account the anisotropy of the material. Anisotropy is induced by crystallographic and morphological textures, and possibly by the spatial distribution of intermetallics. The temperature dependence is introduced through a Zener–Hollomon type term. The resulting anisotropic formability of sheets implies a new approach by adapting the forming limit diagram with a stress based criterion. This approach is confronted and validated by considering the industrial forming of a head clip.

1. Introduction

Zinc exhibits a hexagonal crystal lattice with a high c/a ratio of the Hexagonal Closed Packed (HCP) lattice, inducing a strong structural anisotropy. Alloying elements, such as copper and titanium standardly used in zinc sheets, typically have strong effects on the crystallographic structure as discussed by Zermout et al. (1996), and consequently, on the mechanical anisotropy (Diot et al., 1999). At low concentration, copper is completely dissolved in a (ηZn) phase (Miodownik, 1990), but titanium, precipitates with the eutectic phase $TiZn_{16}$ (Saillard et al., 1981). Moreover, standard rolling conditions lead to a strong texture and to the alignment of intermetallics parallel to the rolling direction. The intermetallics can also be fragmented, depending on the particular rolling configuration and conditions (Fig. 1). Zinc is also known to undergo dynamic recrystallization in forming conditions, even at room temperature (Philippe, 1994). The crystallographic texture shows a significant concentration of c-axes at 20° of the normal to the sheet, in the direction of rolling (Fig. 1) (Philippe et al., 1994a,b).

The formability of zinc has been studied in few publications during the last 60 years, especially in the field of forming processes as described by Piccinin et al. (1976) and developed by Porter (1991).

The most studied formability feature is the bendability of zinc, critical for low temperatures (Philippe et al., 1991). An interesting work overseen by Turk et al. (2008) proposes to determine the most critical parameters on this feature by applying mathematical genetic algorithms which considers input variables like the alloying content and the different rolling parameters. Another recent study steered by Pantazopoulos et al. (2013) illustrates the bendability performances influenced by microstructural features, but the most exhaustive studies can be attributed to Beaujean (1993) and to Wégria (1984), which proved the essential role of the magnesium content to improve the bendability characteristics. In relation to the bendability, the springback after bending is studied by Delannay et al. (2004). The springback anisotropy was evidenced from experimental bending tests in the rolling and transverse directions, and confronted to polycrystalline model simulations.

Few papers analyze the general zinc formability by including the important feature of anisotropy. Some studies as developed by Wégria (1984) insist on the critical role of anisotropy, on an experimental basis. Bramley and Mellor (1967) and Pearce (1968) describe some of the first comparative studies between different anisotropic materials, including zinc, by considering the Hill yield criterion. Mechanical properties have also been studied, looking

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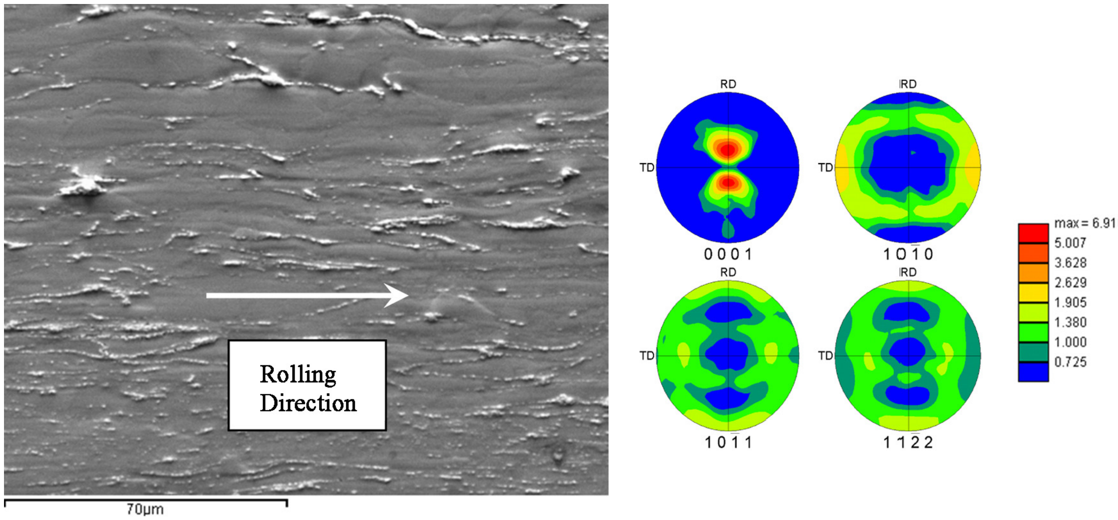

Fig. 1. SEM micrograph of zinc sheet, (RD, TD) plane, and related pole figures determined by EBSD analyses.

at the influence of alloying contents as described by Falzoni et al. (1971) and Neumeier and Risbeck (1971). Another interesting study proposed by Rogers and Roberts (1967) introduces anisotropy features of zinc and titanium subjected to tensile tests and bulge tests. In the case of zinc, the authors emphasize the fact that twinning modes increase as the angle of the tensile axis with the rolling direction approaches 90°. The high sensitivity of zinc to the loading direction (Jansen et al., 2013) is unusual compared to other HCP structure materials like magnesium as proposed by Kaiser et al. (2003) and Huang et al. (2009) or titanium as studied by Hammami et al. (2011) and Huang et al. (2010). In the case of magnesium, some studies show the strong directional dependence of Lankford coefficients whereas the mechanical behavior seems relatively isotropic. In the case of titanium, the Lankford coefficients are extremely anisotropic, and the tensile tests reveal a relative directional anisotropy. Most of the time, the material parameters used in behavior laws are approximated as isotropic by averaging over different directions.

The ICME (Integrated Computational Materials Engineering) methods permit to circumvent some difficulties induced by microstructural inhomogeneities such as the non-isotropic distribution of inclusions and their influence on the mechanical anisotropy as exhaustively discussed by Horstemeyer (2012) and pragmatically studied by Milesi et al. (2010) and Milesi et al. (2011) for specific fatigue problems. Standard polycrystalline models can be used to predict texture evolutions of zinc and titanium as briefly discussed by Funderberger et al. (1997) and more precisely by Philippe et al. (1994a,b) or their effect on mechanical behavior, e.g. the ViscoPlastic Self-Consistent model (VPSC) (Lebensohn and Tomé, 1993). These types of models will not be considered in this study, instead, the model described in this paper considers only the macroscopic point of view, which limits the applicability to a non-evolving anisotropy, but tremendously decreases computation time and allows to easily integrate the behavior law into a finite element software, or introduce it within a formability criterion. The anisotropy is therefore considered here as an intrinsic feature of zinc inherited from the rolling history, and which has a consequence on the formability associated to any forming process.

Few of the formability criteria are adapted to the considered zinc sheets. A first attempt of a generalized anisotropic criterion was analyzed by Funderberger (1992), investigating different hexagonal materials, including zinc. However, the special response of zinc near the pure bi-expansion loading was not captured by the approach. Jansen et al. (2012) and Jansen (2013) propose several standard approaches adapted to the formability of zinc, e.g. an extension of the modified maximum force criterion (MMFC), firstly proposed by Hora et al. (1996) to take into account an inversion of the stress path. The stress based criterion (initially proposed by Arrieux et al. (1982) and developed by Arrieux and Boivin (1987) and Stoughton (2000)) is chosen instead here, for its simplicity to circumvent the difficulties of the high dependency of zinc to strain rate and temperature, and owing to the demonstrated capacity to describe the forming limits anisotropy, as highlighted by Jansen et al. (2013).

The paper is organized as follows. The next section focuses on the anisotropic behavior law and on the possibility to follow the evolution of the Rolling Direction (RD) during a complex forming process, using the so-called fiber vector. This is needed for any anisotropic law which refers to the angle with the RD. In Section 3, experimental forming limits of the investigated zinc sheets are analyzed and described both in the strain and stress spaces. A stress criterion is proposed, in line with that proposed by Jansen et al. (2013). In Section 4, the formability criterion is tested on an industrial forming process, described by a finite element formulation, and predicted failure zones are compared to industrial fracture paths.

2. Anisotropic behavior law

As a first approximation, an isotropic strain hardening law has been tested. Future improvements will consider both anisotropic hardening and Bauschinger effects. However, at this stage of our knowledge, the asymmetry effect has not been investigated for zinc and will be identified in future work by means of reversible bending tests.

The yield criterion chosen is the anisotropic Hill criterion in its quadratic form (Hill, 1948), which seems correctly fitted for zinc alloys (Jansen et al., 2013). Other criteria like that of Cazacu–Barlat (Cazacu et al., 2006) could be investigated in the future, but require more material parameters and specific tests to identify them.

The equivalent stress Eq. (1) is given as a function of the eigen stresses, through the orientation dependent parameters $a(\theta)$, $b(\theta)$, and $c(\theta)$ linked to the Hill 48 parameters (Hill, 1948).

$$\bar{\sigma} = \sqrt{a(\theta)\sigma_1^2 + b(\theta)\sigma_2^2 - 2c(\theta) * (\sigma_1\sigma_2)}. \quad (1)$$