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The effects of the yield surface curvature and anisotropy constants on the axial crush response of circular crush tubes

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ABSTRACT

In this paper, the effects of the yield surface curvature and anisotropy constants on the predicted crush response of aluminum tubes are investigated. The yield function proposed by Plunkett et al. (2008) with two linear transformations is employed in the commercial finite element software LS-DYNA to predict the crush response of the aluminum alloy AA5754-O circular tubes. This yield function represents anisotropy of aluminum alloys accurately by simultaneously capturing the variation of both the yield stress and the R-value with orientation. Dynamic crush simulations of tubes are performed using this yield function with four different yield surface shapes. The same sets of experimental uniaxial yield stresses and R-values along with various sample orientations are considered for determining the anisotropy coefficients of the yield function for each case (the coefficients are different even though the input experimental data is the same). Simulations of axial crush show that the yield surface shape affects the collapse mode and predicted energy absorption characteristics of the crush tube. The analysis shows that the deformation is predominately controlled by balanced biaxial deformation. However, characterization of both the plane strain and pure shear points on the yield surface for energy absorption are also important. The shape and the area of the yield function govern the loading condition, which dictates the deformation and energy absorption. The results demonstrate the importance of the shape of the yield surface in axial crush simulations of structural components using aluminum.

1. Introduction

In the automotive industry, axial crushing of simple geometric structures, such as circular tubes, has been widely studied to understand and predict the performance of structural components. In particular, the usage of lightweight alloys, such as aluminum, has been studied for their implementation into these structural components for their distinctive weight saving and manufacturing advantages. Numerical simulations of these lightweight alloys in axial crush have become an essential tool in product development by reducing the need for multiple experiments to validate the performance. Axial crushing is a difficult phenomenon to simulate due to the large and complex strain paths that the structure undergoes during axial collapsing. Material anisotropy introduced from manufacturing processes presents an additional complexity that affects the development of large strain. Modeling these complex strain paths and material behavior accurately is critical for the implementation of numerical simulations as a product development tool.

Significant research has been performed to accurately characterize the anisotropic behavior of metals. Hill [1–4] introduced yield functions that extended the isotropic von Mises yield criteria to include sheet anisotropy for large strain deformation. Barlat and Lian [5] introduced a phenomenological yield function that coupled stress tensor components together, which showed good agreement with results from polycrystalline plasticity theory. Their yield function captured anisotropy of sheet through the Lankford Coefficients (R-values) that were obtained from uniaxial tensile tests in three different directions. Lian et al. [6] showed that yield surface shape has a significant effect on forming limit diagrams (FLD).

Yield functions served a key role in the accuracy of finite element (FE) predictions of large strain deformation observed in sheet metal forming and crashworthiness [7]. Lademo et al. [8] investigated yield functions for their appropriateness in constitutive models for simulating the mechanical behavior of aluminum alloys. They concluded that although the yield functions proposed by Hill [2] and Barlat and Lian [5] improved the description of the material anisotropy, the anisotropic behavior of the material was not completely captured. Barlat et al. [9] proposed another yield function, known as Yld2000 function, which

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Table 1
Chemical composition of aluminum alloy 5754-O (wt%) [38].

Al	Mg	Mn	Cr	Fe	Si	Cu	Ti	Zn
Bal	0.75	0.25	0.10	0.40	0.85	0.70	0.10	0.15

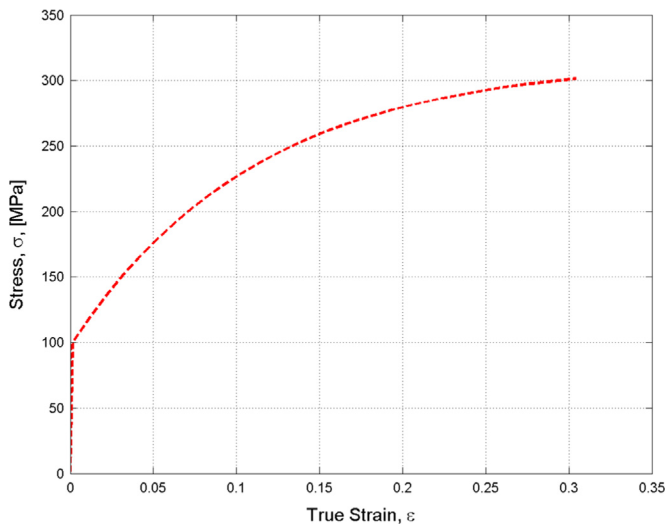

Fig. 1. Experimental stress-strain curve for AA5754-O [38].

performed a single linear transformation on the stress tensor. By introducing a linear transformation, the so-called R-values and yield stresses (as a function of sheet orientation) were better captured while maintaining a continuously convex yield function. Yoon et al. [10] implemented Yld2000 into a FE code and showed excellent agreement between predictions and experiments of aluminum cup drawing.

Cazacu et al. [11,12] extended Yld2000 to incorporate multiple linear transformations on the stress tensor. They also introduced the material tension-compression differential effect that is pronouncedly observed in hexagonal close packed (HCP) alloys, such as magnesium and titanium, and moderately observed in body-centered cubic (BCC) and face-centered cubic (FCC) alloys, such as steel and aluminum. The yield function using two linear transformations is often referred to as CPB06ex2 [12]. Dassappa et al. [13] showed that multiple solutions could be obtained for fitting R-values and yield stress orientations for continuously cast AA5754, using the CPB06ex2 yield function. However, even though every set of CPB06ex2 parameter were able to capture the material anisotropy (R-value and yield stresses w.r.t. the rolling direction) they resulted in substantially different FLD predictions due to the differences in the yield surface curvatures.

Concurrently, significant work was performed to understand axial crush mechanics of simple geometries. Alghamdi [14], Olabi et al. [15], and Yuen and Nurick [16] have presented an extensive review on the study these simple geometries in energy absorption

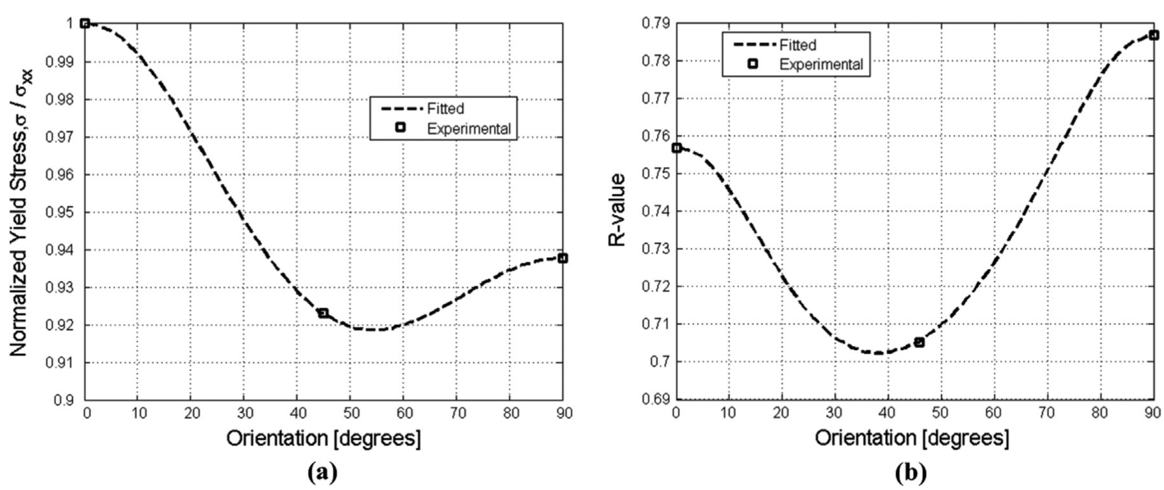

Fig. 2. Experimental and fitted variations in (a) normalized yield stress and (b) Lankford coefficients as a function of orientation for AA5754-O [38].

Table 2
Material parameters used in yield functions.

a	C_{11}	C_{22}	C_{33}	C_{12}	C_{13}	C_{23}	C_{44}
3.00	-13.3867	-13.1294	-13.8268	-14.3002	-12.8721	-12.9936	1.2475
	C_{11}'	C_{22}'	C_{33}'	C_{12}'	C_{13}'	C_{23}'	C_{44}'
	-13.3867	-12.6138	-12.4926	-11.9990	-13.2326	-13.2500	-0.9998
a	C_{11}	C_{22}	C_{33}	C_{12}	C_{13}	C_{23}	C_{44}
8.00	-0.5969	0.3756922	0.8482	-1.2344	-0.7846	-0.4337	1.2281
	C_{11}'	C_{22}'	C_{33}'	C_{12}'	C_{13}'	C_{23}'	C_{44}'
	-0.5969	-0.464962	-0.9691	-1.9075	-2.2045	-2.1731	1.5149
a	C_{11}	C_{22}	C_{33}	C_{12}	C_{13}	C_{23}	C_{44}
12.00	4.0850	3.6354	4.3201	2.2818	3.5011	3.8487	1.6331
	C_{11}'	C_{22}'	C_{33}'	C_{12}'	C_{13}'	C_{23}'	C_{44}'
	4.0850	4.1831	6.1634	3.0073	4.9341	4.4892	1.2735