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In-plane biaxial compression and tension testing of thin sheet materials

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ABSTRACT

Detailed experimental data on the behavior of textured sheet metals under compressive loading is important to describe their tension–compression asymmetry. This is particularly needed for materials that exhibit a strength-differential effect, or in cases where the Bauschinger effect occurs. So far, there is no systematic work describing the third quadrant in the 2D stress space under biaxial compressive loading. This paper presents a new device for biaxial, compressive in-plane testing of thin sheets. Biaxial and uniaxial compression experiments are carried out in the strain controlled device, analyzing the behavior of deep drawing steel sheets with and without skin-pass treatment. Moreover, in order to allow for the experimental description of the yield surfaces, biaxial tensile tests are performed. Detailed numerical validations and experimental strain analysis both for the new specimen for biaxial compressive testing and for the cruciform specimen for biaxial tensile testing show that reasonably homogeneous strain distributions can be achieved. The combined experimental and numerical method presented here allows to evaluate the tension–compression asymmetry of thin sheet materials. The results for the skin-passed condition clearly exhibit a tension–compression asymmetry, which highlights the necessity of biaxial compression tests already in the as-received material condition. The biaxial compression test opens a pathway to a more detailed analysis of the flow behavior of thin sheets under biaxial compression loading.

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1. Introduction

Some material processing steps, like skin-pass rolling (also called temper rolling) in the final stage of a sheet rolling process (Hoggan et al., 2002; Fang et al., 2002) strongly affect material flow behavior. One reason to apply skin-pass rolling is to eliminate the yield phenomena associated with Lüders bands formation (Yoshida et al., 2008). Such sheet metal forming processes are generally associated with multiaxial load cases. An experimental characterization of complex loading conditions is beneficial for the identification and/or verification of material models to be used in numerical simulations (Kuwabara, 2007). It is also essential for an accurate description of the yield surfaces of anisotropic sheet metals. Well advanced methods for sheet metal characterization have been developed, such as uniaxial and biaxial tension tests, as well as shear tests. Especially the multiaxial tension loading tests using cruciform specimens are well established tools for specifying and verifying anisotropic yield criteria used in Finite Element (FE) simulations, as can be seen in Green et al. (2004), Hannon and Tiernan (2008), Kuwabara et al. (2002), Lin and Ding (1995) and Merklein and Biasutti (2013). Recently, an ISO standard for a biaxial tensile testing method using a cruciform test piece was published in ISO (2014).

Little attention has been paid to compression tests on sheet metals, especially under multiaxial loading. In-plane compression tests are not commonly used in sheet metals because of buckling issues. However, a more detailed understanding of compressive behavior is needed for reliable FE modeling of phenomena like the strength-differential effect (SDE) or the Bauschinger effect. Several biaxial, compressive tests have been proposed both for bulk material as well as for sheet materials. Bridgeman (1946) performed experiments with rectangular bulk blocks, using two independent hydraulic presses. Khan and Wang (1990) presented an experimental setup for proportional and non-proportional loading paths, where a rectangular bulk specimen first undergoes a uniaxial compression up to a finite deformation and then the biaxial compression state is reached. Shimizu (2007) developed another

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biaxial compression test for bulk materials that allows for arbitrary strain path changes without unloading. In this experimental setup, a rectangular block is placed between four dies that can be controlled independently.

For sheet metal testing in biaxial (and also in uniaxial) compression loading, the specimen geometry plays a major role because the thickness of the material is small compared to the other dimensions. In-plane uniaxial compression testing can in principle be accomplished using standard-size tension specimens if buckling is prevented by suitable mechanical constraints; such methods have been summarized in Boger et al. (2005). For this kind of test, a correction function that takes into account frictional and biaxial effects arising from the supporting force must be determined by numerical investigations. The correction has to be performed for each material individually, which is a time consuming procedure. Because of the specimen geometry, this approach cannot be used for biaxial compressive testing. A similar approach for uniaxial testing has been proposed in Kuwabara et al. (2009). Tozawa and Nakamura (1971) used adhesively bonded sheet laminates that were machined into cubic samples for biaxial compression tests. Barlat et al. (1997) and Maeda et al. (1998) used similar sheet laminate samples for an experimental investigation of the yield surfaces of Al-Mg alloy sheets with different crystallographic textures. One disadvantage of the laminate specimens is that it is difficult to determine the stress–strain relations accurately because of the friction between the single layers and the friction between the specimen and the dies. Moreover, the specimens are prone to buckling and delamination, and non-uniform deformation can arise when the dies are not perfectly parallel. Kulawinski et al. (2011) used a cruciform specimen to investigate the stress–strain behavior for different load paths, including biaxial compression. To prevent buckling during the biaxial compression test, supporting plates were developed to clamp the specimens, which led to considerable amounts of friction.

Based on the state of art in uniaxial and biaxial compression testing of sheet metals, this work presents a systematic study using an optimized specimen geometry and an advanced test rig. This paper is focused on the tension–compression asymmetry of a steel sheet grade DX56 (1 mm thickness) in a skin-passed, and, for comparison, a non skin-passed condition. In addition, a low carbon steel sheet DC04 with 2 mm thickness is analyzed to investigate the effect of sheet thickness on the test results. Additional tests in uniaxial tension, biaxial tension and simple shear are carried out to fully describe the yield surface in all four quadrants of the σ_{RD}–σ_{TD} plane.

2. Experimental procedure

2.1. Materials and characterization methods

The materials used in this work are a deep drawing steel grade DX56 with 1 mm thickness and a low carbon steel grade DC04 with 2 mm thickness. Both materials are widely used for automotive body parts. The DC04 grade was annealed and subjected to a final skin-pass by the manufacturer. The DX56 grade was provided by Voestalpine Austria in a non-(DX56-N) and a skin-passed (DX56-S) condition, produced from the same material batch. The final skin-pass (DX56-S) was performed with an equivalent plastic strain of 1.16%. The material properties in uniaxial tension (0°, 45°, and 90° with respect to RD) are summarized in Table 1. Both yield strength and anisotropy (as characterized by the *r*-value) increase after skin-passing; the work hardening coefficient *n* is slightly reduced.

Table 1
Mechanical properties of the tested materials measured in uniaxial tension.

Material	Tensile direction (°)	$\sigma_{0.2}$ (MPa)	n[a]	r[b]
DC04	0	191	0.21	1.87
	45	204	0.19	1.19
	90	198	0.20	2.13
DX56-N	0	117	0.29	1.61
	45	121	0.28	1.54
	90	129	0.29	1.86
DX56-S	0	155	0.25	1.85
	45	161	0.25	1.31
	90	156	0.26	2.11

[a] Determined between true plastic strains of 0.05 and 0.2
[b] Average value between true plastic strains of 0.05 and 0.2

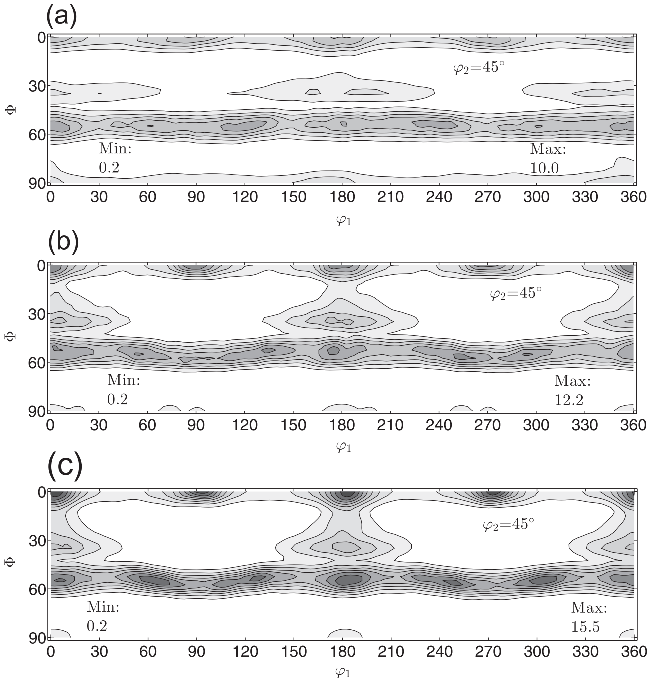

Fig. 1. Euler angle representation of ODFs computed from the measured diffraction data along the $\varphi_2 = 45^\circ$ sections. All angles are given in degrees. a) DC04, b) DX56-N and c) DX56-S.

The effect of skin-passing on the texture of the DX56 material was characterized by XRD. The three incomplete pole figures of the planes {220}, {200} and {211} were measured at half sheet thickness. Orientation distribution functions (ODFs) were computed from the raw data, Fig. 1. For comparison, the texture of the 2 mm material DC04 is shown in Fig. 1(a), and the textures of both DX56 materials are shown in Fig. 1(b) and (c). All three materials exhibit a γ-fiber (i.e., the ⟨1 1 1⟩ direction is parallel to the sheet normal direction, which is indicated by the high intensities for $\Phi \approx 55^\circ \pm 5^\circ$ in the cut of the ODF data at $\varphi_2 = 45^\circ$). This is a characteristic feature for rolled steel sheets. A texture strengthening can be observed during skin-passing, even though the plastic strain is low. Skin-passing of DX56 leads to an increase of the intensities at $\varphi_1 = 0^\circ$, $\varphi_1 = 60^\circ$, $\varphi_1 = 120^\circ$, …on the γ-fiber. Strengthening at the same orientations were also reported for a low carbon steel grade during uniaxial tension and plane-strain tension (Clausmeyer et al., 2013). These changes in texture are also likely related to the higher *r*-values after this final manufacturing step.

2.2. Biaxial compression apparatus

The new test rig has been designed for use in a conventional universal testing machine. In this study, a servo controlled

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