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Effect of the Slenderness Relation on In-Plane Deformation in Stack Compression Tests

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Abstract

In forming technologies and their simulation, knowing the flow curve characteristic of the material is an essential parameter. Acquiring this knowledge is particularly challenging for sheet materials in high strain ranges. It is well-known that friction and geometric relationships have a distorting effect on the flow curves, thus compensation is necessary. However, the geometric ratio can not only influence the formation of the flow curve, if our material shows anisotropic behaviour. In our research, using compression tests, we examined the deformation relations of deformed specimens through digital imaging methods. The stack compression test is widely used to determine the flow curve in a broad range of large deformation. During the test, several disk specimens with the same geometric characteristics were stacked on top of each other to form a final test piece, and then compression tests were conducted on these assemblies. We found that at low values of the geometric ratio (0.1 in our study), the proportion of plastic, planar principal strains indicating anisotropic behaviour is greater than at higher geometric ratios (0.5 and 1.0 in our study).

Keywords: *disk compression test, stack compression test, anisotropy.*

1. Introduction

The stack compression tests are mentioned in early literature with the aim of extending the measurable range of material behaviour to include larger deformations beyond those covered in tensile tests. Additionally, Barlat et al. [1] proposed describing the biaxial material behaviour with the normal direction compression of sheets.

Accurate knowledge of flow curves is essential for various sheet forming technologies. Understanding higher deformation ranges, which are often encountered during sheet forming, poses significant challenges. To gain insight into these ranges, several methods have been developed, such as uniaxial compression testing, hydraulic bulge testing, the Watts–Ford-test, or the stack compression test [2]. Merklein and Kuppert [3] were among the first to conduct stack compression test, which we also employ in our study.

While each method has its advantages and disadvantages, friction and geometric considerations are particularly troublesome in methods involving methodology of compression. Regarding friction, it is commonly assumed to be constant during testing, a notion challenged by Coppieters et al. [4], Kraus et al. [5] and Gil et al. [6], both considered the friction coefficient to be variable with pressure during testing. Siebel és Christiansen et al. [7] proposed a flow curve equation compensation for geometric considerations in compaction testing. During the Watts–Ford-test Graf et al. [8], Chermette et al. [9] and Banabic et al. [10] also made recommendations regarding the relationship between various geometric dimensions of the test specimen.

Geometric correction is not only important for proper approximation of flow curves but also for describing anisotropic plastic behaviour, where the test specimen deforms non-uniformly in different directions. Anisotropic behaviour is known from fracture tests, where the ratio of cross-directional and thickness-directional deformations of the sheet specimen is referred to as the anisotropy factor. However, in mechanically equivalent biaxial tensile stress states achieved with uniaxial compression, the sheet may behave differently. In the literature, the proportion of in-plane deformations measurable during experiments conducted under such stress states is termed biaxial, or two-directional, anisotropy factor [1]. It is necessary, however, to examine the dependence of this measure on factors known to influence the formation of flow curves during compression. These factors include friction and the length-to-diameter ratio. In this article, we focus on the effect of the latter factor.

Fig. 1. *Instron4482 electromechanical universal testing machine.*

Fig. 2. *The polished pressure plates.*

2. Preparation and execution of the experiments

The tests were conducted on sheet material labelled DC04, which, due to its ferritic microstructure, endows it with good formability properties, making it widely used in various industries.

2.1. Presentation of test specimen

The test specimens were fabricated from sheet metal. Cutting was performed using the Trumpf TruLaser Cell 7020 system, a 4 kW diode laser-based equipment. The cutting accuracy of the device is ±0.02 mm. Nitrogen gas was used during cutting.

Considering the cross-section of the selected test specimen to be circular, its nominal diameter is 10 mm, and its nominal thickness is 1 mm. The precise dimensions of diameter and thickness were determined from the average of fifty test specimen geometries. The rolling direction of the sheet was always marked.

2.2. Presentation of testing equipment

The experiments were conducted using the INSTRON 4482 electromechanical universal testing machine, capable of applying tensile, bending, shear, and compression loads, and determining strength and plasticity characteristics. The INSTRON 4482 testing machine is shown in Figure 1.

We equipped the machine with cylindrical pressure plates, with a diameter of 40 mm and a thickness of 20 mm. The pressure plates were made of highly alloyed tool steel designated as K110, which had an average hardness of 57 HRC after heat treatment. The pressure surfaces were polished, as shown in Figure 2. This was necessary to reduce the friction between the workpiece and the tool.

2.3. Positioning and lubrication

During the experiment, it is crucial to ensure the uniaxial alignment of the specimens. Manual positioning is not sufficient, so we created a positioning unit using additive manufacturing on the Craftbot flow idex xl device. The material used is BASF's PLA, and it consists of two halves. When closed, the surfaces of the test specimens and the inner walls of the positioning device create point-like contact, reducing the degree of uniaxial error. The unit and the disk assembly it arranges can be seen in Figure 3 displaying the unit's length-to-diameter (l/d) ratio.

The surfaces of the test specimens in contact with the pressure plates were treated with Luba 21 high-pressure lubricant. However, no lubrication was applied to the surfaces of the test specimens in contact with each other, aiding in promoting bulk material behavior.

2.4. Execution of compression tests

The experiments were conducted for three different cases. In the first case, a single disk (length-to-diameter ratio: 0,1) was used, in the second case, five disks (length-to-diameter ratio: 0,5), and in the third case, ten disks (length-to-diameter ratio: 1,0) were stacked and subjected to compaction tests at a constant strain rate, with a threefold frequency of measurements. A test specimen between the pressure plates can be seen in **Figure 4.**

The displacement of the crosshead occurred at a rapid traverse speed of 3 mm/min, while the preload did not reach 250 N. This value corresponds to compressive stresses of 3–10 MPa, which is less than 5% of the yield strength but sufficient to stabilize the assembly before the main loading begins. Subsequently, the crosshead proceeded depending on the height of the assemblies, ensuring the following relationship is fulfilled.

$$v = h/10, \qquad (1)$$

where v is the displacement speed of the crosshead, and h is the initial height of the currently compacted assembly.

In **Figure 5** the assemblies are visible after compaction. The compression of each assembly continued until we approximately reached half of the initial height.

2.5. Scanning and measurement of test specimens

Subsequently, the scanned images of the compacted test specimens were obtained using the Vinyl Open Air device. The equipment employs a single camera with a resolution of 1.3 megapixels and capable of achieving an accuracy of 6 µm. The test specimens were fixed to the machine's magnetic table. The point cloud generated during scanning is depicted in **Figure 6**. The point clouds contain the coordinate points of the entire assemblies after compaction.

We reduced the number of elements in the scanned point cloud, helping to speed up modelling. The model based on the simplified point cloud is shown in **Figure 7.**

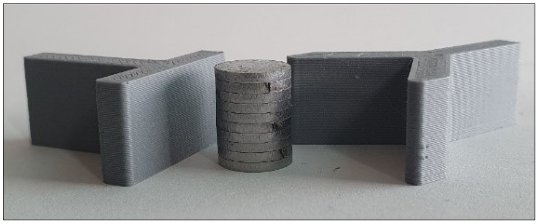

Fig. 3. *Positioning unit and the stack made by it.*

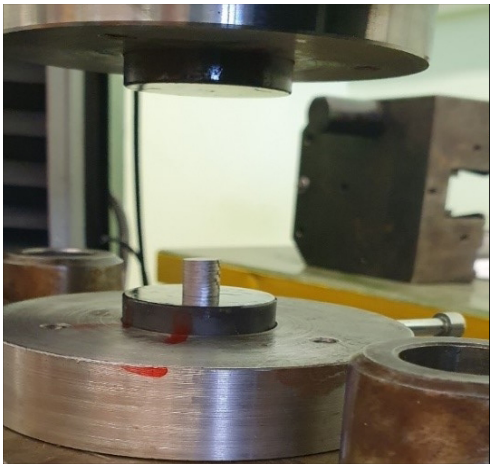

Fig. 4. *Execution of the compression tests.*

Fig. 5. *The stacks after compression test.*

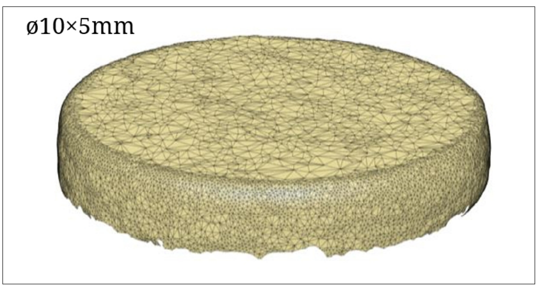

Fig. 6. *The scanned specimen.*

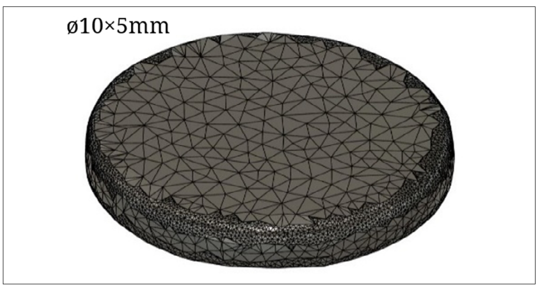

Fig. 7. *The model based on the simplified point cloud.*

3. Results

The necessity of scanning plays a role in measuring deformations occurring during compression tests. While we can directly calculate the thickness-directional deformation (ε_v) of the test specimens during testing from the values of the crosshead displacements (taking into account the stiffness of the machine), the in-plane deformations remain hidden between the pressure plates. (For the calculation of thickness-directional deformations, we used the statistical sheet thickness as the initial size.)

By measuring the in-plane deformations, we can infer the anisotropic behavior of the test specimens. An example of this can be seen in **Figure 8**, where the parallel (ε_0) and perpendicular (ε_{90}) logarithmic deformations to the rolling direction are clearly different. A difference of nearly one millimeter is observed between certain dimensions of the test specimen at a 0,5 l/d ratio.

The calculation of effective, true plastic deformations (ε_f) is possible based on the knowledge of the flow condition (assumption), for which in this study, we applied the Hill'48 theory **[11]**. For this purpose, only the in-plane principal deformations and the average normal anisotropy factor (R value) obtained from tensile tests need to be known, which, based on our previous measurements, can be assumed to be 1.706 for the DC04 material. In **Table 1**, β expresses the ratio of in-plane principal deformations, which is also equal to the value of the biaxial elongation anisotropy factor (r_b) :

$$r_b \equiv \beta = \frac{\varepsilon_{90}}{\varepsilon_0} \qquad (2)$$

The values of the anisotropy factors for tensile testing and biaxial elongation can be illustrated by **Figures 9** and **10**.

During tensile tests, the normal anisotropy factor varies slightly as deformation progresses, as shown in **Figure 9.** Approximating with a linear function, we provided the average of three measurements in the text.

Based on **Figure 10,** the value of anisotropy associated with biaxial elongation can also be considered variable depending on the geometric ratio or the effective deformation.

4. Conclusions

A convenient method for capturing flow curves in large deformation ranges is compaction testing. However, its execution requires geometric and frictional corrections.

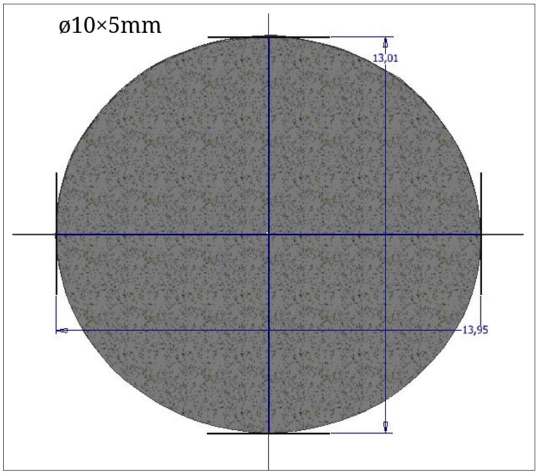

Fig. 8. *The difference in diameter between the rolling direction and the perpendicular direction.*

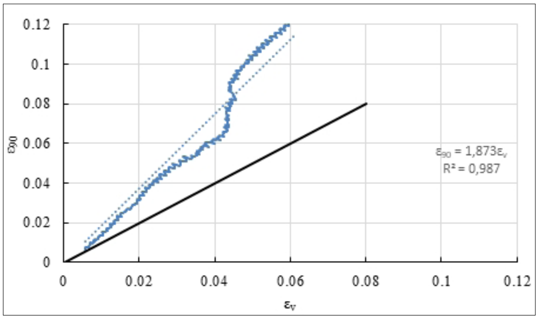

Fig. 9. *Anisotropy (R) Value Determined from Tensile Testing.*

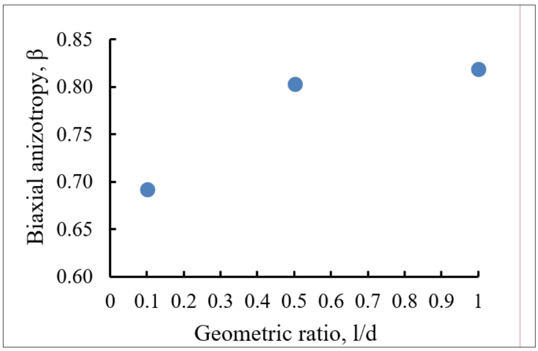

Fig. 10. *The change in biaxial anisotropy (R) value as a function of the l/d ratio.*

Table 1. *The measured and calculated deformations*

l/d	ε_v	ε_0	ε_{90}	ε_f	β
0.1	–0.355	0.241	0.167	0.476	0.69
0.5	–0.633	0.356	0.286	0.748	0.80
1.0	–0.675	0.370	0.303	0.784	0.82

In our study, we examined whether it is necessary to consider the geometric ratio when determining the biaxial anisotropy factor or if it only distorts the shape of the flow curves. We conducted our investigations on test specimens with l/d ratios of 0.1, 0.5, and 1.0. Deformations were derived from changes in mid-diameter using digital image correlation.

Our results indicate that the measured value of the biaxial anisotropy factor is slightly distorted in the examined geometric ratio and deformation range when the length-to-diameter ratio is small (in our case, 0.1). However, significant differences are not observed for length-to-diameter ratios of 0,5 and above.

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