This is the published version of a paper presented at 30th Nordic Seminar on Computational Mechanics (NSCM30).

Citation for the original published paper:


N.B. When citing this work, cite the original published paper.

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Numerical Analysis of Anisotropic stiffness of thin Al-foil in multiple material directions based on Experiments

Conference Paper · October 2017

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NUMERICAL ANALYSIS OF ANISOTROPIC STIFFNESS OF THIN AL FOIL IN MULTIPLE MATERIAL DIRECTIONS BASED ON EXPERIMENTS

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Key words: Thin foil, Aluminium alloy, Anisotropy, Symmetry plane, Young’s modulus

Summary. Numerical analysis have been performed on tensile test experiment data to evaluated the performances of a 9 microns thick aluminium foil. The identification of the anisotropic material properties is based on tensile tests performed in 11 different angles from 0° to 90° from the rolling direction. By least square fitting and extrapolation to zero load the elastic modulus is, as opposed to the general belief, proven to be very close to the expected bulk values for this specific material. The elastic modulus is shown to be anisotropic with a stiffness variation of about 15%. Minimum stiffness is obtained in around 45° from the rolling direction.

1 INTRODUCTION

Thin foils and composite layers of aluminium are utilised in products for containers for beverage, food, medicine, etc.1,2. In these applications the thicknesses of the aluminium foil varies a lot and the thinnest are of the order of only a few microns. The application development and design depends increasingly on accurate predictive engineering methods. Thus, a thorough understanding of mechanical properties is required. Many experimental test and theoretical analyses have been performed to characterise the mechanical response2,3,4. A severe obstacle is that the mechanical response of thin samples are sensitive to geometrical effects, sample size and imperfections like wrinkles, weak grain, thickness variations etc. Therefore, the correct representation of mechanical properties and complete understanding of the mechanical behaviour involves delicate work of experimental test combined with theoretical studies. The numerical analysis is an important...
part needed to make correct evaluation of test result.

The aim of this work is to thoroughly characterise aluminium foil by the use of physical testing and computational method. The earlier studies on this specific aluminium foil limited to uniaxial loading in the manufacturing direction i.e. Rolling Direction (RD). In this study, the anisotropic properties and material behaviour are investigated.

2 NUMERICAL APPROACH AND RESULTS BASED ON EXPERIMENT

The experimental measurements were performed on strips of this aluminium foil with the cross section dimensions of 15 x 100 mm\(^2\) and a thickness of 9 microns, which is delivered from the production line at Tetra Pak. The samples were cut with incremental angles of 10° from the RD. An uniaxial tensile test were performed on the samples from different angles, see Fig. 1 for the result. Further details regarding the experiment is published in the work by Käck and Malmström\(^4\).

![Image](image.png)

**Figure 1**: Experimental tensile test results for 0° (RD), 45° and 90° (TD)\(^4\)

The handling of thin samples and correct performing during the test is quite challenging because of the extremely small thickness. Even though a very careful attention is paid to the test performing details, it is still difficult to correctly capture the initial elastic response. It is well know that Young’s modulus for isotropic poly-crystalline aluminium is around 69 to 71 GPa, depending on the different alloying elements. In many engineering applications of thin aluminium foil Young’s modulus is taken to be 40-45 GPa, referring to tensile test results performed on foils similar to the one tested by\(^1,5\). It is by us assumed that the rather low moduli are chosen as an engineering practicality and are deliberately including the plastic deformation that is initiated at very low load. It could also be caused by misalignment of the sample, slippage in the grips or devices used for measuring
the displacements or similar. The mere thinness of the foil as such does not seem as a reasonable argument. It is argued that as long as the material contains more than 10 to 20 atomic layers, e.g. more than 100nm, bulk properties may be assumed\textsuperscript{6}. This motivates the present detailed exploration of the obtained data and its characterisation of the material properties. From the performed test the force and elongation were measured for each direction, and the corresponding stress and strains are calculated. The stretching before the final rupture is rather homogeneous and below 10\%. Further, the cross sectional area is unknown, which makes the, e.g. Cauchy stress unknown. Because of this, engineering stress and strain is used in this pilot study. The general stress and strain relationship on incremental form is written $d\sigma_{ij} = C_{ijkl}d\epsilon_{kl}$, where $C_{ijkl}$ is the tangent stiffness of the material. The stiffness tensor $C_{ijkl}$, being a rank 4 tensor, transforms according to the following

$$C'_{pqrs} = \beta_{pi}\beta_{qj}\beta_{rj}\beta_{ls}C_{ijkl},$$

(1)

where the $\beta_{ij}$ are the directional cosines. For the rotation in the $x_1,x_2$-plane all indices assume values 1 and 2. The Einstein summation rule applies. Here the assumption is that the material is orthotropic and subjected to plane stress, thus the stiffness tensor is represented by the four relevant components, $C_{1111}$, $C_{1122}$, $C_{2222}$ and $C_{1212}$ in the principal coordinates $x_1$ and $x_2$. The components $C_{1112} = C_{1222} = 0$. In non-principal directions in the $x_1,x_2$-plane, the components $C_{1112}$ and $C_{1222}$ may be non-zero. The relation in Eq. (1), gives the uniaxial component as,

$$C'_{1111} = C_{1111}\cos^4(\theta_n) + (C_{1122} - 2C_{1212})\cos^2(\theta_n)\sin^2(\theta_n) + C_{2222}\sin^4(\theta_n),$$

(2)

where the angle $\theta_n = \theta_0 + n\Delta\theta$ with $n = 0,1,...,10...$ The angle $\theta_0$ is the anti-clockwise angle from the rolling direction to the principal direction of the material and $\Delta\theta = 10^\circ$. The least square set of constant parameters $(A,B,C,\theta_0)$ is implicitly given by Eq. (2), where $A = C_{1111}$, $B = C_{1122} - 2C_{1212}$, and $B = C_{2222}$. Three linear equations allow elimination of A, B, and C from the least square requirements. A final non-linear equation is solved iteratively for $\theta_0$. The solution for $\theta_0$ is not unique and therefore the iterative procedure was locked into a small range of plausible angles. The range $-20^\circ$ to $20^\circ$, gave realistic solutions for all tensile test directions given by $n = 0,...,11$. The set $(A,B,C,\theta_0)$ represents the tangent stiffness and is a function of the strain. The result is displayed in Figs. 2 a) and b), where $E'$ and $C'_{1111}$ is shown.

3 CONCLUSIONS

1. Detailed analysis of tensile tests on a 9 micron thick aluminium foil show that the stiffness practically assume bulk values.

2. The material is slightly anisotropic with around a $\pm7\%$ variation.
Figure 2: a) Elastic modulus $E' = C'_{1111}$ as $\delta \to 0$ for different loading directions vs the RD. The dashed vertical delimiters show the principal directions. b) Uniaxial tangent stiffness at different elongations, $\delta=1, 2$ and $3$ mm. Both are as a function of the angle $n\Delta\theta$. The angle $\theta_0$ is visible on the left side of the diagram.

3. The primary principal direction is initially close to $-14^\circ$ from the rolling direction and decreasing with increasing deformation to around $-2^\circ$ at 3 mm elongation.

REFERENCES


