MEASUREMENTS OF EFFECTIVE ELASTIC MODULUS IN WOUND ROLLS OF THIN ALUMINUM FOIL

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Abstract

Elastic properties of wound rolls are used as an input for simulations of stress-strain state in the roll after winding in order to optimize quality of foils. The effective elastic modulus in direction perpendicular to the layers of foil is challenging to measure because it is dependent on interlayer pressure and is generally much smaller than the bulk elastic modulus of the material. Normally, stacks of many layers of foil are pressed in order to determine the interlayer-pressure dependence on effective elastic modulus. In this study, a similar test was carried out using multiple methods including standard compress tests with strains evaluated by using video extensometer as well as digital image correlation of the stack surface and instrumented indentation method. The results given by all methods were compared. Moreover, multiple stack thicknesses were tested in order to evaluate the influence of stack size on the effective modulus. The tested foil was made from aluminum alloy AA8079 and was 13 μm thick.

Keywords: Wound rolls, aluminum, mechanical properties, compression test, instrumented indentation

1. INTRODUCTION

Aluminum foils are commonly used in packaging and automotive industries and are valued for their unique physical properties, food safety and affordable costs. Very thin foils are often desirable for their unique properties as well as lower costs due to less raw material. It is challenging to produce very thin aluminum foils in high quality. One of the challenges is to keep the thin foil sufficiently flat. During the technological process of casting and subsequent rolling uneven foil profile can be produced (convex or concave profile). During subsequent winding of the foil the parts of the profile that are thicker stretched more in order to keep overall shape of the coil cylindrical and stable. Uneven plastic and elastic strains in the foil plane can be formed in the technological process. Elastic strains can be then transformed into plastic strains during heat treatment.

Numerical modelling of winding and heat treatment of the coil is used to simulate formation of strains in the wound-in foil. Results of the numerical modelling are used for minimising defects and increasing flatness of final foil. In order to properly characterise material properties of wound-in foil it is necessary to consider material in the coil as elastic transversely isotropic with effective elastic modulus in direction perpendicular to the foil plane and bulk elastic modulus in other directions. The effective elastic modulus is pressure sensitive and encompasses the stiffness of sandwich structure composed of aluminum, air, rolling oil layers and the effect of mutual contact of surface asperities. The effective modulus decreases with decreasing foil thickness.

A compression test of stack of foils is commonly used in order to determine the effective modulus dependence on interlayer pressure for measured foil [1,2]. Normally, stacks with at least 200 foil layers are used to carry out the compression test [3]. The layers of foils are cut from already wound coil and piled up to form a stack of sufficient thickness. During the test a stack is pressed between two flat hard plates and the distance between the plates as well as the pressing force is measured. The main problem of this method in case of thin aluminum foils is that layers of already curved foil in the coil are flattened as the example stacks are produced and the already locked-in asperities from adjacent foils are broken and the compliance of the material in this direction is altered.

In this paper a measurement of effective elastic modulus using a standard compression test with more than 50 mm tall stack of foils is compared to modified measurements with the deformation of the foils in the stack measured by digital image correlation (DIC) using multiple thinner stacks. Moreover, the effective modulus was also measured using indentation method as this method allows using small stacks of foils. The aim of this study is to show the influence of the sample stack thickness on the effective modulus of wound-in foil and to compare different methods for determining the effective modulus of wound-in foil.

2. MATERIAL PROPERTIES

The foil used in this study was made in AL INVEST Bridlicna, a.s. by continuous casting and was rolled until final thickness 13 μm was reached. The material of the foil was AA8079 aluminum alloy (AlFe1Si type) with bulk Young modulus 52 800 MPa, Poisson ratio 0.34 and yield stress 160.1 MPa. The foil manufacturer provided stacks of foils with approx. cubic shape 54.2 × 50.2 × 50.7 mm.

3. EXPERIMENTAL SETUP

3.1. Compression method

The measurements of effective modulus were carried out using a static testing machine. One compression test was performed using a large stack with thickness 54.2 mm. Compound strains of the whole stack were measured by video extensometer. The stack was loaded with constant speed 1 mm/min until the maximum force 20 kN was reached.

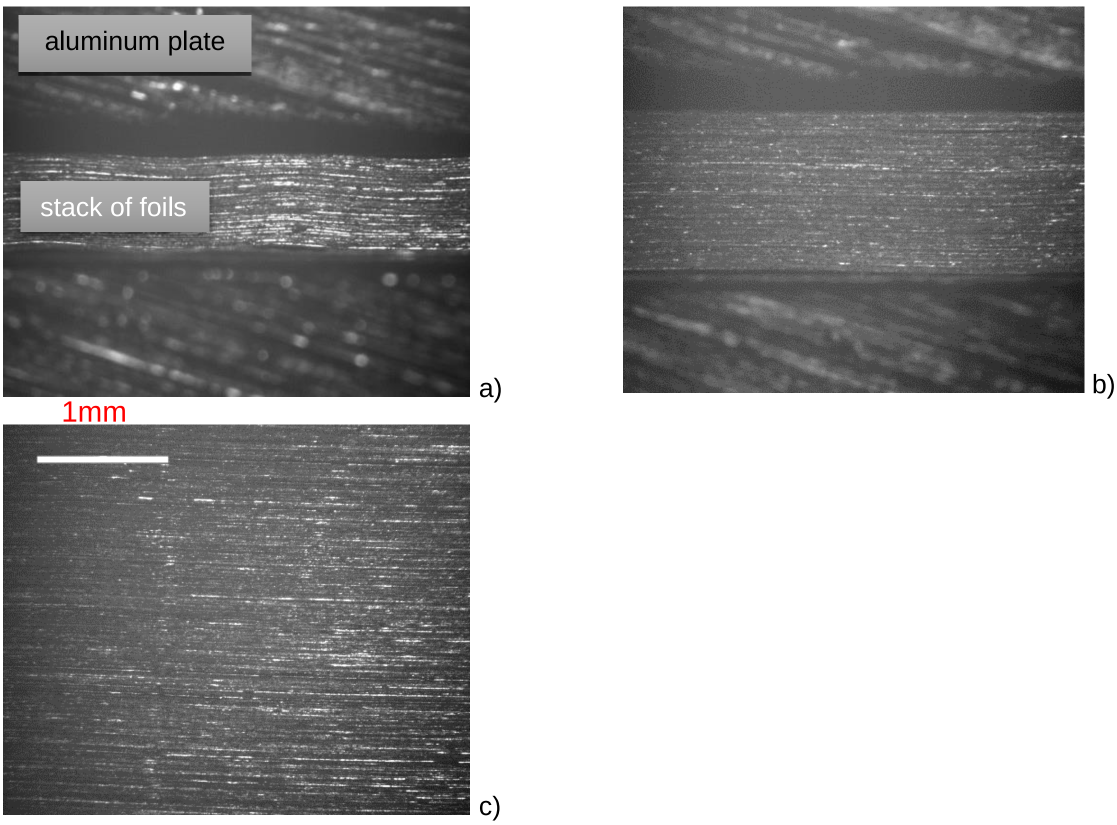

Figure 1 Images from the FLIR camera for thicknesses of stack of foils of a) 0.87 mm, b) 1.48 mm, c) 5.72 mm

Subsequently, stacks of foils with overall thickness 0.87, 1.48 and 5.72 mm were tested in order to evaluate how the effective modulus is influenced by stack thickness. Each stack was placed in between two 11 mm tick plates with metallographically smoothed surface made from aluminum alloy to provide good support and inserted into the testing machine. Each stack was then loaded with constant speed of 0.1 mm/min until maximum force 10 kN, which corresponded to approx. 4 MPa pressure, was reached. The unloading was carried out with the same speed. The surface of the stack was recorded using digital camera FLIR Black Fly with inline telemetric lens during the whole test. The record was used to evaluate pressure strains using digital image correlation method (DIC). Images from the camera are shown in **Figure 1**. The thickness of each stack analysed with DIC was smaller than the overall stack thickness. Values of analysed thicknesses for all stacks of foil are summarized in **Table 1**.

Table 1 Overall stack thicknesses and thicknesses analysed by DIC

Thickness of stack (mm)	0.87	1.48	5.72
Analysed thickness (mm)	0.65	1.00	2.2

3.2. Instrumented indentation method

The effective modulus was also measured using instrumented indentation method on the CSM CPX NHT machine. A stack of foils was placed on 11 mm thick aluminum plate and indented using a sphere indenter with radius 100 μm. Continuous multi-cycle (CMC) indentation with ten steps and maximum force 10 N was used (see **Figure 2** for illustration). New stacks with thickness 1.48, 2.48 and 5.72 mm were prepared and measured to evaluate possible stack thickness dependence, three indents were made per stack to evaluate measurement variance. The effective modulus was evaluated from the unloading phase for each step in CMC process using Oliver-Phar method [4,5]. The corresponding stress was calculated according to Tabor's formula $\sigma_r = \frac{H}{C}$, where σ_r is representative stress, H is hardness of the material and *C* is a constraint factor [6]. The recommended value by [6] of constraint factor *C* = 3 was used in this study.

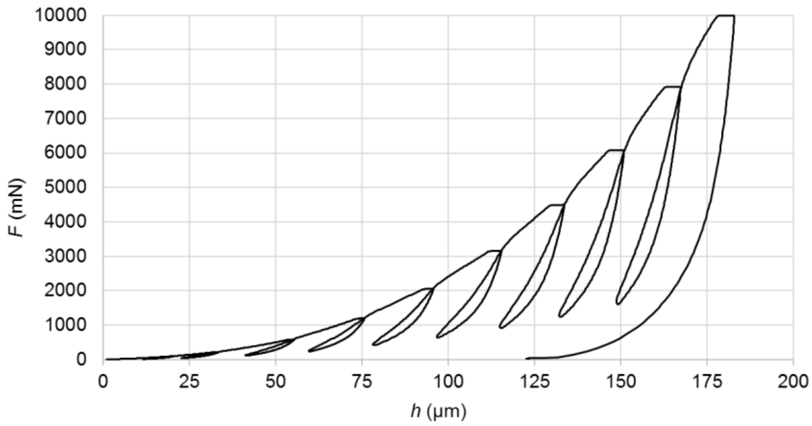

Figure 2 *F*-*h* curve ofCMC indentation of stack of foils with thickness 2.48 mm

4. RESULTS AND DISCUSSION

The stress-strain record obtained from the compression test was transformed into effective modulus (E_r)–interlayer pressure relationship. The observed data showed hysteresis behaviour, so the effective modulus evaluation was split into loading and unloading phase. The results are shown in **Figure 3,** resp. **4** for loading, resp. unloading phase of the compression test. The thickness of the stack has influence on the effective modulus in both loading and dun loading phase of the test. The stacks with thickness 1.48 and 5.72 mm have linearly rising trend in the whole range of measured pressures, whereas the effective modulus measured in the thinnest stack flattens out at stress approx. 2.5 MPa. Both thicker stacks are approx. 2.5× more compliant than the thinnest stack in the loading phase. All the stacks behave stiffer in the unloading phase because of already compacted layer interfaces after the loading phase. The thinnest stack is 4-8× stiffer than the thickest one in the unloading phase.

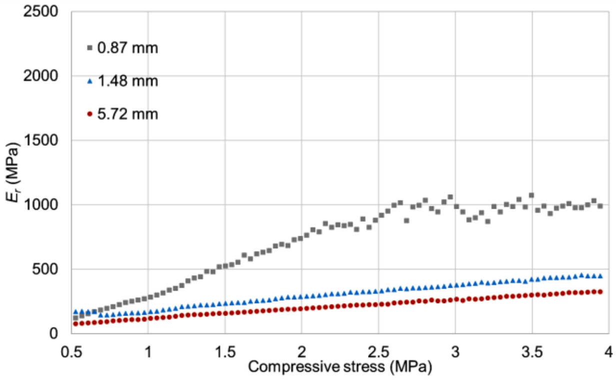

Figure 3 A relationship between effective modulus and compressive stress for *loading* phase of the compression test with tested stack thicknesses 0.87, 1.48 and 5.72 mm

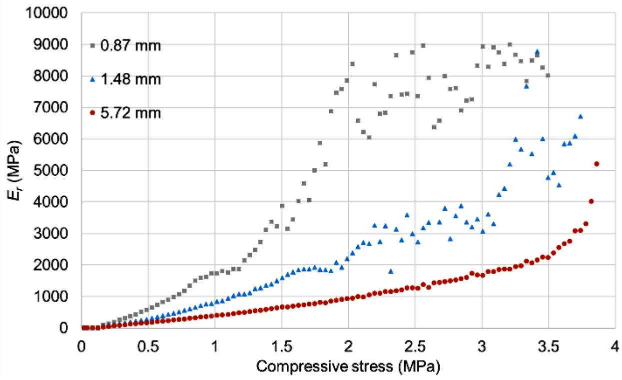

Figure 4 A relationship between effective modulus and compressive stress for *unloading* phase of the compression test with tested stack thicknesses 0.87, 1.48 and 5.72 mm

The inconsistency of results between the loading and unloading phase is caused by deformation of foil surface asperities, the sample stack becomes therefore more compact and the material response in the unloading phase is less influenced by interlayer interfaces. An illustration of stack surface before the experiment was carried out with gaps between individual layers of foil can be seen in **Figure 5**. Larger gaps with thickness of approx. one foil layer were also occasionally observed. They contribute to measured higher compliance of thicker stacks.

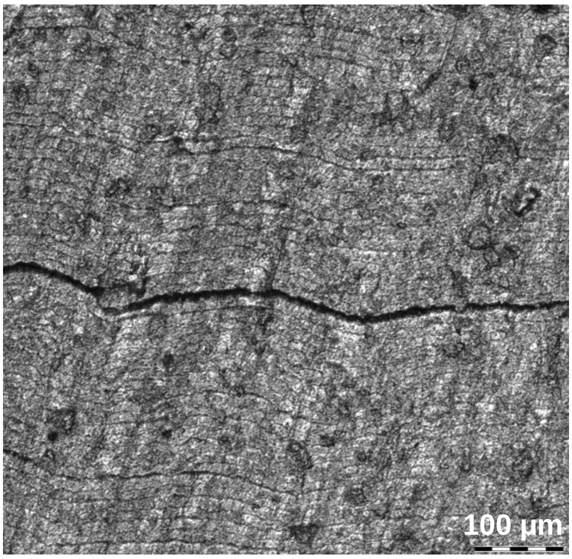

Figure 5 A surface of the stack of foils with visible gaps between individual layers

The results of indentation measurements are shown in **Figure 6**. It can be seen that the thinnest tested stack of foils with thickness 1.48 mm is the stiffest and the thickest one with thickness 5.72 mm is the most compliant, which is in line with results of compression tests. The difference between 2.48 and 5.72 mm is small. The variance of results between individual indents within the same stack is negligible.

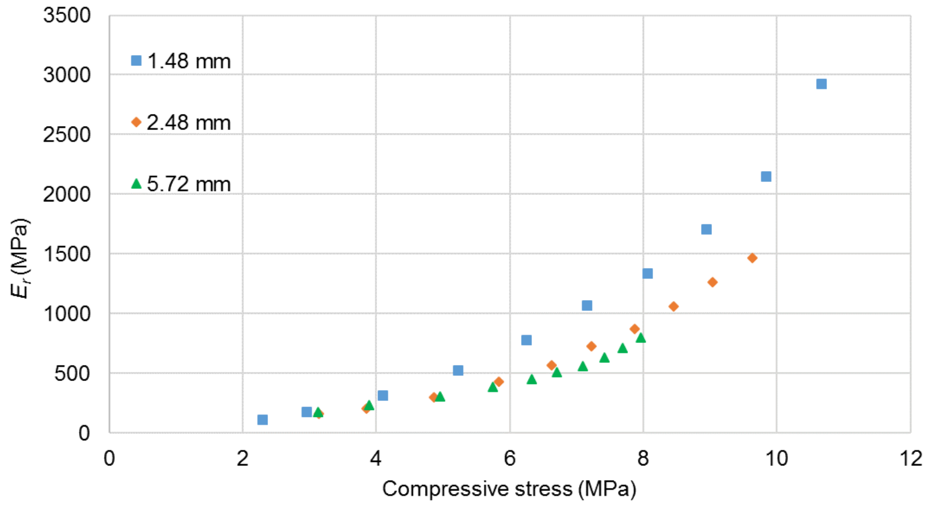

Figure 6 A relationship between effective modulus and compressive stress of the indentation test with tested stack thicknesses 1.48, 2.48 and 5.72 mm

The results from both compressive stress with DIC and the indentation test were compared with a standard compression test with video extensometer (see **Figure 7**). It can be seen that both the loading phase of compression test with DIC and the indentation test correspond to the compression test with video extensometer. The effective modulus given by the unloading phase of the compression test with DIC is approx. 4-6x higher compared to other results. The results of loading phase of compression test with DIC, instrumented indentation and compression test with video extensometer are similar.

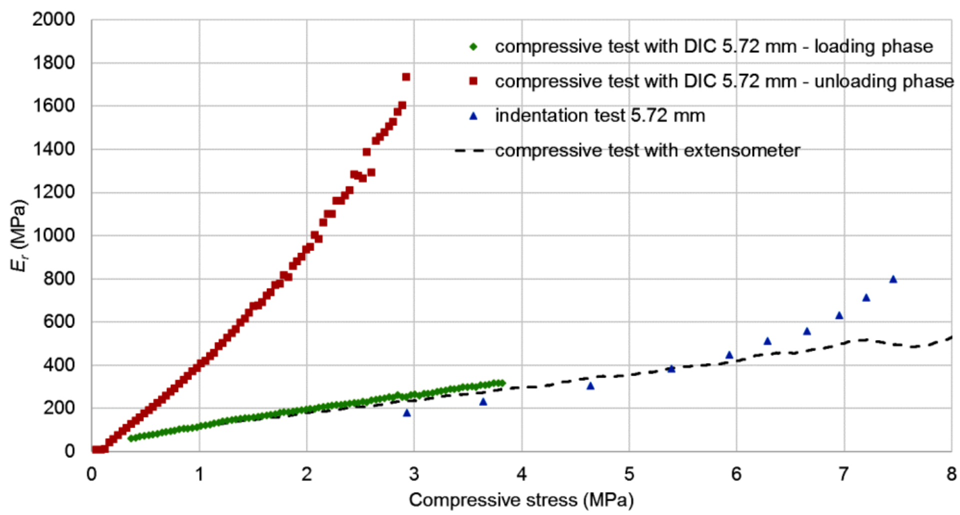

Figure 7 A comparison of measurements of effective modulus using compression test with DIC and video extensometer and indentation method with stack size 5.72 mm was used for DIC and indentation method

5. CONCLUSION

Compression tests of stacks of foils with strains measured by digital image correlation (DIC) and video extensometer as well as indentation tests were performed in this study in order to determine effective modulus of the material. Multiple stack thicknesses were used in order to assess the influence of stack thickness on the effective modulus. The following conclusions can be drawn as a result of the research:

1) The effective modulus is 4 to 6 times higher in the whole range of measured compressive stresses in the unloading phase compared to the loading phase of the compression test with DIC.
2) The effective modulus is higher for thinner stack sizes in both loading and unloading phase of the compression test with DIC as well as in instrumented indentation test.
3) The indentation method gives similar results to both loading phase of the compression test with DIC and video extensometer. The indentation method must be further investigated whether it is a suitable method of evaluating effective modulus and different indenter sizes and foil thicknesses should be tested.
4) Numerical simulations of stresses in wound in foil should be done using effective modulus of both loading and unloading phase of compression testes serving as boundary values.

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