

Tensile test and finite element simulation of coarse-grained thin aluminium sheets

A Szlancsik^{1,*} and D Varga¹

¹ Department of Materials Science and Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary

*E-mail: szlancsik.attila@gpk.bme.hu

Abstract. The aim of this work was to investigate the ability of finite element simulations applied to specimens containing only a few grains for tensile testing. For this purpose, two different finite element models were created: one with individual grains with individual flow curves generated by viscoplastic self-consistent (VPSC) calculations and one with uniform material properties throughout the cross-section of the sample. In comparison of the two models with experimental tensile tests, the following conclusions can be yielded. The measurement and the simulation with individual grains have the same deformation shape. Also, the mechanical properties (yield strength, tensile strength and elongation at break) were within 10% error. However, if the measurement results were compared to the simulation with homogeneous material, it showed an error up to 53%. Therefore, it can be stated that the tensile tests of these types of specimens can be simulated, but only if the grains are modelled individually.

1. Introduction

Miniaturization, a significant trend in contemporary times, initially garnered notice within the nuclear industry by the late 1970s [1–3]. Due to the ongoing process of miniaturization, various fields like medical applications [4], microelectronics [5] and additive manufacturing [6,7] utilize thin films and sheets. In these instances, it has been well-documented that the mechanical properties undergo significant changes compared to those of the bulk material [8–10]. In mechanical loading scenarios, such as shaping, actuation, and fixation of such materials, the significance of free surface and size effects grows, also traditional continuum mechanics methods may diminish in validity under these circumstances [11]. Additionally, if the thickness of the component contains only a few grains, variations in the response to applied forces between parts can be substantial. Consequently, maintaining consistency in mechanical performance can prove challenging. Disregarding these effects in industrial design may lead to unforeseen issues, such as incorrect or too expensive solutions for small components. Many well-known phenomena in forming technology, such as plastic failure, contraction, texture formation, etc., require reconsideration as the ratio between the component and grain size decreases significantly [12]. In theory, the mechanical properties of micro components are influenced by four parameters: grain size, the quantity of grains within the specimen's thickness, specimen thickness, and the existence of free surfaces. When the grain size exceeds a few micrometres, reducing it generally enhances strength, a relationship commonly described by the Hall-Petch relationship [13,14].

Due to the difficulty of measuring miniaturised samples, new measurement methods have been developed. This resulted in the development of miniature specimens of different sizes of tensile specimens since the dimensions of the specimens are not defined in a standard [15]; therefore, the dimensions are determined according to the need and availability of the materials. A new measuring method has also been developed, namely the small punch test [16,17], which can be used to determine



the fracture strength [18] and mechanical properties [19,20] (yield strength and tensile strength) of the given specimen. The inverse finite element method is employed for determining the behaviour of materials under uniaxial tensile testing, specifically the true stress vs. true plastic strain curve. Husain et al. [21] developed an inverse finite element method, with the help of which the small punch test results give an adequate prediction of the true stress-strain behaviour and become comparable with the results of the standard tensile test.

Kumar et al. [22] simulated miniaturised tensile specimens using 2-D finite element analysis. The material parameters used were determined from a standard uniaxial tensile test. The results of a standard specimen and a miniaturised specimen were compared, and it was found that the value of the tensile strength was 2-4.5% lower in the case of the miniaturised specimens. Fülöp et al. [23] investigated ultrathin metal sheets experimentally and through simulation. The effect of the surface grains was examined in relation to the total grain number. In their finite element simulation, they used the single crystal approach for multi-crystal analysis, and their goal was to analyse ultrathin sheets based on crystal plasticity and to verify the predictive ability of the applied finite element simulation. The results showed that the yield stress depends on the number of grains in the thickness direction, and due to the different crystal orientations, the deformation was not uniform under homogeneous tensile stress.

The goal of Kumar et al. [24] was to determine the minimum amount of material required for the properties of the miniaturised specimen to be comparable to that of the standard specimen. For this, finite element simulation was also used, and it was found that the yield stress, tensile strength and elongation values stabilised for a thickness of 0.25 mm, which corresponds to a thickness/grain size ratio of 6, 3.4 and 1.5 in the case of 20MnMoNi55, CrMoV steel and SS304LN materials.

It can be seen from the previous articles that many different approaches have been tried to determine the relationships between bulk materials and materials with only a few grains. However, no procedure has yet been created that could reliably establish this relationship, so the first step in our work is to examine whether the finite element simulation is suitable for replacing cumbersome and in many ways difficult to perform or reproduce measurements. To this end, we first carry out tests that can be reliably reproduced, and then use these to validate our finite element model. Using this model, even the complicated load conditions of the built-in components can be tested in the future.

2. Materials and methods

2.1. Experimental methods

In our experimental work, we used 1 mm thick and 10 mm wide Al99.8 strips. As a first step, the strips were annealed at 570°C for 30 min and then cooled in water. Then, the strips were subjected to an 12% deformation using an Instron 5965 universal material testing machine with uniaxial tension. The previously annealed and cold formed strips were heat treated again to induce recrystallization at 570°C for 30 minutes and then cooled in water. After heat treatment, 10 specimens with a width of 6 mm and a gauge length of 50 mm were produced by machining. The microstructure of the specimens was visualised by etching. The composition of the aluminium macro-etching solution is listed in Table 1.

Table 1. Composition of the aluminium macro-etching solution

Component	Distilled water	Nitric acid (65%)	Hydrofluoric acid (40%)	Hydrochloric acid (37%)
Ratio (Volume %)	18	16	16	50

After etching, the formed grain structure was examined with an Olympus SZX16 stereomicroscope in order to reproduce it by finite element simulation (Figure 1. (a)). The resulting specimens were subjected to tensile tests on an Instron 5965 universal material testing machine at a crosshead speed of 3 mm/min at room temperature. The electromechanical testing machine continuously recorded the load (F) and displacement (Δl) values during the test. These values were then plotted on a diagram in order to evaluate the measurements. First, the engineering stresses and engineering strains were calculated

from the measured data, and then the yield strength ($R_{p0.2}$), tensile strength (R_m) and elongation at break (A) were determined.

2.2. Simulation

In order to simulate the tensile test of the specimens, a model was established using MSC Marc Mentat finite element analysis software. The specimen geometry was identical to the measured one, and the tension was applied with two rigid plates at the end of the specimen with glued contact. One plate was fixed, while the other moved with 3 mm/min. The 3-D model contained 11708 hexahedral elements, with an average side length of 0.41 mm and four elements in the thickness direction. Two different simulations were created. In the first one, the individual grains were selected, and four different material types were assigned to them randomly in order to simulate the specimens which were investigated previously (Figure 1.).

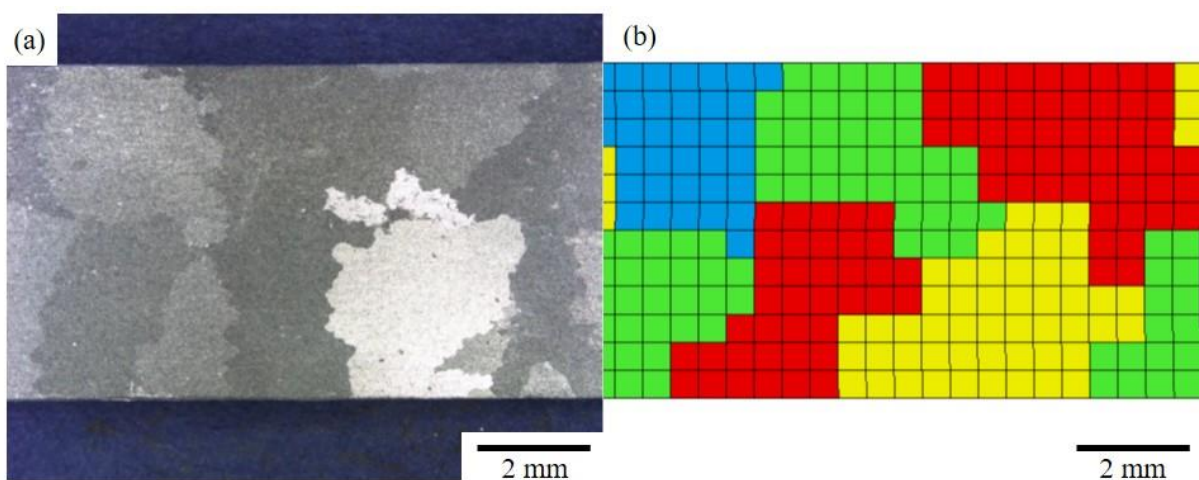


Figure 1. (a) Stereomicroscopic picture of the specimen after etching, (b) the individual grains selected in the finite element model. The colours represents the orientations as follows: red – orientation I, yellow – orientation II, green – orientation III and blue – orientation IV

The material properties in this case were obtained from a viscoplastic self-consistent (VPSC) calculation [25]. In order to get the flow curve of a single grain, the deformation field was given for the software, and only one element was defined in it. The Voce hardening law was used with the material properties given in Table 2. The four different flow curves were created with four different orientations of a single crystal. The investigated orientations were given by Bunge angles in degrees, which were as follows: (I) 0-0-0, (II) 10-0-0, (III) 20-0-0 and (IV) 45-0-0.

Table 2. Material properties of the Al99.8 used in the VPSC simulation

Elastic stiffness (GPa)	E11, E22, E33	E12, E13, E23		E44, E55, E66
	106.75	60.41		28.34
Voce hardening parameters (MPa)	τ_0	τ_1	θ_0	θ_1
	7.5	10.5	220.0	16.5

The other simulation assumed homogeneous material in the entire cross-section of the specimen. The flow curve of the material was given by equation (1)

$$\sigma = 22.2 + 112 \cdot \varphi^{0.416} \quad (1)$$

where σ – is the flow stress in MPa and φ – is the plastic strain. In the case of both simulations, the Young's modulus was 70 GPa, and the Poisson ratio was 0.33. Also, the Cockroft-Latham damage model was used with a 0.43 element removal threshold.

3. Results

In order to compare the results from the tensile tests and the simulations, the data points have been plotted in a common diagram (Figure 2.). It can be seen that there is a large difference between the two simulations. It shows the necessity to model the individual grains and to take into account the different deformations in those grains. Not only is the stress – strain curve higher than the measurement, but it can withstand more than twice the deformation before failure. However, with similar damage parameters, the model which contained the grains individually breaks in close alignment with the measured samples. Figure 3. depicts the total equivalent plastic strains at 12% engineering strain in case of the simulations and also a picture of a sample during measurement. The difference between the two types of models is significant. If the grains are neglected, the total equivalent plastic strain is homogeneous within the sample, which is to be expected since this is the reason why the specimens are designed in this way. However, if the grain size and the sample size are close to each other, the deformation becomes inhomogeneous. This inhomogeneity causes some grains to deform more, thereby reaching the critical deformation and breaking earlier. Also, the edges of the measured specimen are uneven, and this unevenness is also well represented by the simulation containing individual grains.

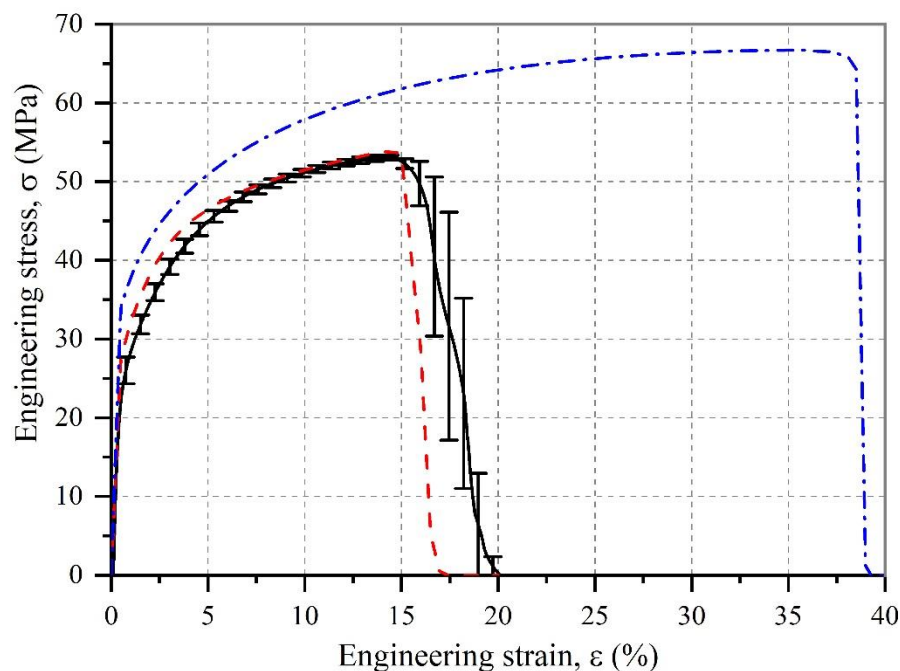


Figure 2. The engineering stress – engineering strain curves for the measurement (black – continuous line), simulation with individual grains (red – dashed line) and simulation with homogeneous materials (blue – dashed-dotted line).

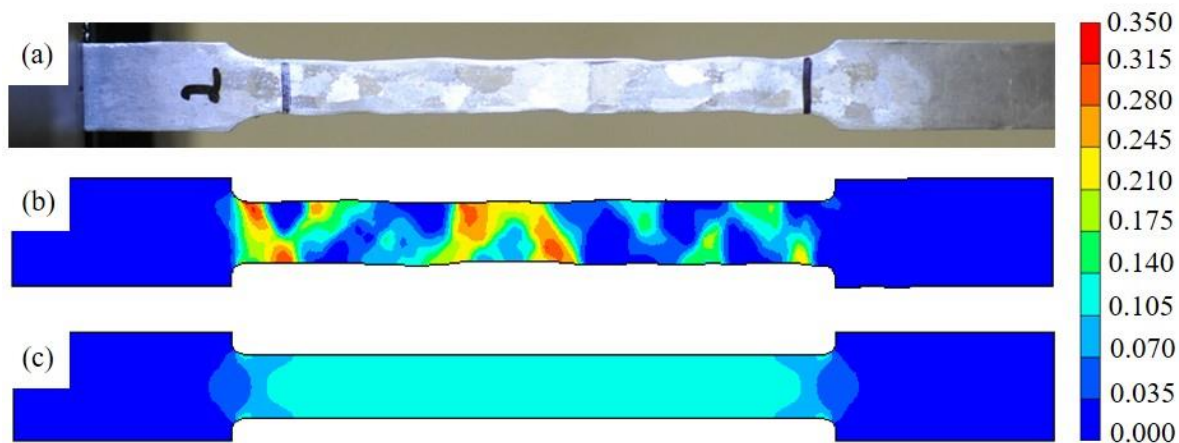


Figure 3. (a) Sample 2 during the tensile testing, (b) simulation with individual grains at 12% engineering strain, (c) simulation with homogeneous material at 12% engineering strain. In case of the simulations, the colours represent the total equivalent plastic strains.

Table 3. contains the mechanical properties determined with measurement and simulation. The percentage error between the mean measured value and the simulation results has been calculated. It can be seen that the simulation with individual grains is in good agreement with the measurement; only the elongation error is slightly bigger than 10%. The results from the simulation without grains are not in good agreement with the measurement results; namely, the elongation error exceeds 53% which is huge. The yield strength and the tensile strength are also above 20% error, which is unacceptable in this case.

Table 3. Mechanical properties obtained from measurements and simulations. The percentage error was calculated between the mean value of the measurements and the simulations.

	Measurement	Simulation (individual grains)	Error	Simulation (homogeneous material)	Error
R_{p0.2} (MPa)	27.0 ± 0.9	29.9	9.7 ± 3.0 %	35.9	24.8 ± 2.5 %
R_m (MPa)	52.7 ± 0.6	53.8	2.0 ± 1.1 %	66.7	21.0 ± 0.9 %
A (%)	18.2 ± 1.3	16.5	10.3 ± 7.9 %	38.8	53.1 ± 3.4 %

4. Conclusion

The aim of our work was to investigate the capabilities of the applied finite element simulation of the tensile test of specimens containing only a few grains. For this purpose, two different finite element model was created: one with individual grains with individual flow curves, which were created by viscoplastic self-consistent (VPSC) calculations and one with homogeneous material properties in the entire cross-section of the specimen. The two models were compared with experimental tensile tests, and the following conclusions were drawn:

- The deformed shape of the specimen in the measurement and in the case of the simulation model with individual grains was similar.
- The specimens with few grains have different behaviour compared to the polycrystalline specimens, and their tensile tests cannot be simulated assuming bulk, homogeneous material.
- In case of the simulation with individual grains, the mechanical properties (yield strength, tensile strength and elongation at break) were within 10% difference, whereas when simulated as a homogeneous material, the difference was as high as 73%.
- It was shown that the individual grain simulation model is suitable for the simulation of tensile tests of specimens with few grains.

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