

Measurement and prediction of deformation in plane strain compression tests of AA5182

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Abstract

This paper concerns the numerical prediction and experimental measurement of the distribution of strain in a plane strain compression test by means of a gridded insert. The insert was engraved with a 1×1 mm grid pitch and was embedded in an AA5182 sample. The tests were performed at 400°C with a reduction ratio of about 20% and at a strain rate of 0.7 s^{-1} . A thermocouple was used to record the temperature during the test. After the test, no detachment was observed between insert and sample, suggesting a close contact between them. The shape of the grid after deformation was analysed and the in-plane component of the plastic strain calculated and compared with the numerical results obtained through finite-element modelling of the test. In a comparison between experimental data and the results of a finite element (FE) model of the test that assumed perfect tool alignment, the fields of temperature agreed very well, whilst that for the in-plane component of strain was reasonable but inaccurate. However, significant misalignment of the tools was found in the experiments (a common occurrence in plane strain compression testing). When comparison was made with an FE model that included the geometry of the tool misalignment, the agreement was excellent. The paper discusses these effects and others such as the influence of 3D effects in the modelling.

Keywords

Grid, insert, plane strain compression, aluminium alloy, AA5182, finite element.

1. Introduction

The rolling process always results in a very heterogeneous deformation across the thickness of the slab, which in turn implies the development of a gradient of deformation textures.^[1] This heterogeneity of deformation and texture affects the final rolled sheet leading to well known industrial problems such as *earing*. To help overcome these issues, the rolling process has been the subject of many studies over the past years, focusing on microstructural evolution and modelling. However these studies are problematic due to the fact that during rolling the material is locally affected by a range of temperatures, strains and strain rates that are difficult to simulate in a controlled way. For this reason, plane strain compression tests are commonly used to represent the material behaviour in thermo-mechanical processes such as hot rolling. In a modern compression testing machine, important parameters such as the imposed strain, strain rate and temperature can be controlled to pre-set values or functions. The output in terms of nominal stress-strain values, usually at pre-set values of strain rate and temperature, provides a definite description of the behaviour of the material unencumbered by the complexity of what happens to it in the rolling mill. In this context, it is important to evaluate the temperature and the deformation along the centre-plane of the specimen, which is the area used for texture and microstructural studies. It is also important to establish the degree of confidence associated with the use of finite element models to predict such quantities.

Although the gross mechanics of the plane strain compression (PSC) test appear to be rather simple, the material deforms inhomogeneously, the details depending upon external parameters such as the quality of tool lubrication and the material deformation characteristics themselves.^[2] Metallurgical studies require that a small sample be taken from a part of the deformed test specimen where deformation is fairly uniform so allowing the correlation between the observed metallurgical changes and the local mechanical state. Typically, after a compression test has been performed, a small specimen (usually 10×10 mm) is cut from the

middle of the sample and used for texture and microstructure studies. The analysis of this specimen requires the values of the components of the strain as input, and these values are usually considered constant and equal to the applied ones. This assumption does not take into account the whole-field values of the strain and the possible variations within the deformed area. Mirza and Sellars^{[3][4]} observed an inhomogeneous strain field after modelling hot PSC tests of stainless steel and aluminium and showed that the heterogeneity of deformation is affected by the initial geometry of the specimen but is independent of the type of material and strain rate. In this scenario it is essential to validate the local values of strain obtained through FE modelling and investigate the effects of common experimental problems such as tool misalignment that affect the distribution of the strain.

Due to the physical conditions associated with the compression test (high temperature, large deformation and high strain rate) it is not possible to employ traditional methods of measurement. In some cases, an embedded pin has been used to reveal deformation in rolling^{[5][6]}. The disadvantages of this technique are the detachment between pin and material and the limited area where the deformation can be measured. Grids have been used to measure the deformation in hot rolling^[7] and cold extrusion^[8] and in general to calculate large strains during compression at room temperature^[9].

Timothy *et al.*^[7] used an engraved insert embedded in a sample in a rolling experiment and the grid survived large deformation. If an insert is used it is essential that the insert does not detach from the specimen during deformation, since in that case the grid would not be representative of the deformation of a sample without insert. Moreover, the grid has to be strong enough to survive high pressure, large deformation and oxidation at high temperatures.

In this work, a gridded insert was used with the engraved surface facing the centre-plane of the specimen. The components of the logarithmic plastic strain were calculated by analysing the grid after deformation and were compared with the results from FE models.

2. Experimental Work

The tests were performed on a SERVOTEST thermomechanical compression machine which is capable of producing temperatures of up to 1100 °C and strain rates of up to 100 s⁻¹.

Four identical samples were centrally slotted in order to embed the 30 mm long insert (fig. 1 top). One face of the insert was polished to 1 µm finish and engraved with a regular 1×1 mm grid pitch using a height gauge equipped with a carbide tipped scribe. The average depth of the grooves was measured with a mechanical profilometer resulting in 50 µm on average, whilst the average width of the grooves composing the grid was 0.2 mm. The insert and slot were machined so that a transition fit was achieved. The gridded face of the insert was located on the centre-plane of the specimen. To avoid damage to the grid when assembling the sample, the workpiece was first warmed up in order to allow the cold insert to slide in easily.

Two slots were machined on the sides of the samples to accommodate the holders of the compression machine. Two of the samples gave similar results whereas the remaining two could not be considered because the grid did not survive the test.

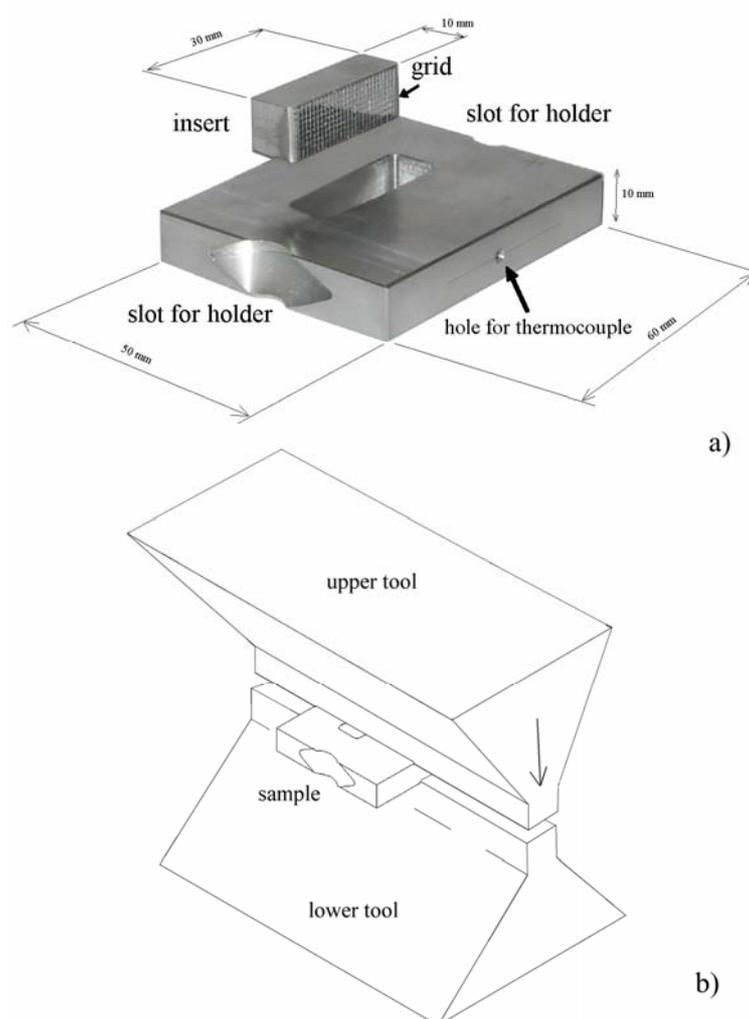


Figure 1 – a) View of the sample with the gridded insert. The insert was hand-engraved with a $1 \times 1 \text{ mm}$ grid pitch. A thermocouple was used to record the temperature throughout the test. b) Schematic of the tools and the sample in a plane strain compression test.

The temperature was measured during the test by means of a type-K thermocouple inserted in a hole accurately drilled so that, when fully inserted, the thermocouple head was very close to the centre-plane of the specimen. It is important that the hole for the thermocouple does not reach the gridded surface of the insert as shown in fig. 2.

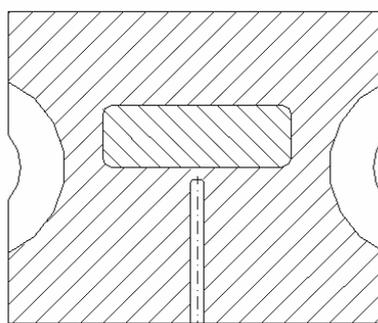


Figure 2 – Section of the specimen. The thermocouple hole does not touch the gridded surface to avoid damage to the grid due to extruded material.

Failure to do so would cause damage to the grid due to extrusion of material from the insert towards the hole. It was observed in early tests that the resulting grid could be damaged in the central area which is the most significant for the purpose of this work. The thermocouple was

put in place and secured by punching the immediate surrounding of the hole in order to avoid any loss of contact between the head of the thermocouple and the material during the test.

The aluminium alloy used for this work (table 1) was a commercial alloy with a high percentage of magnesium. The specimens were machined from a billet that had been produced through a complex industrial rolling process.

AA5182 composition	Al	Mg	Fe	Zn	Si	Mn	Cu	Cr	Ti
Weight %	93.2-95.8	4-5	max 0.35	max 0.25	max 0.2	0.2-0.5	max 0.15	max 0.1	max 0.1

Table 1 – Composition of 5182 aluminium alloy

The sample was heated up to 400°C following the temperature-time curve in figure 3, then held at 400°C for 60 seconds and eventually compressed at a strain rate of 0.7 s⁻¹ and a reduction ratio of 20% (that corresponds to an applied plastic strain of approximately 0.22).

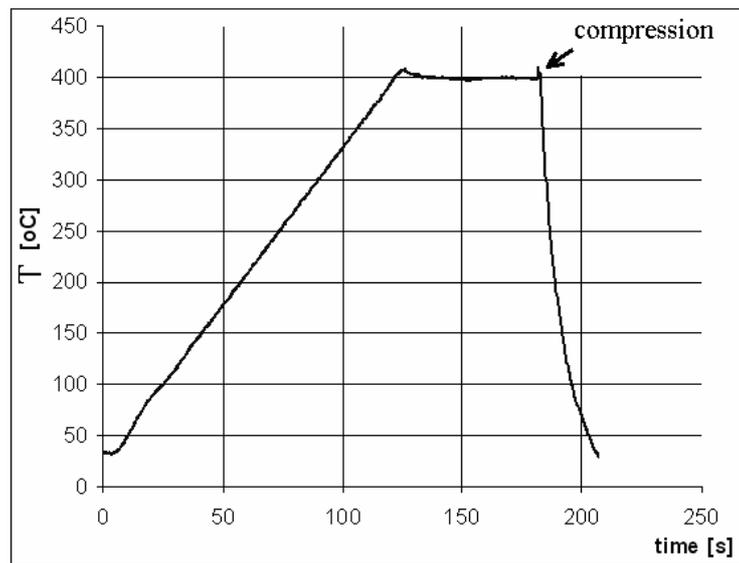


Figure 3 – Temperature recorded by the thermocouple during the test. The compression itself lasted less than a second.

The compression itself was performed by the upper tool of the machine while the lower tool was stationary. The temperature of both tools was the same as the sample. Graphite powder was used to lubricate the sample-tool interface.

Figure 4 shows one of the samples after deformation. As can be seen, there was no detachment between insert and work-piece in both transverse and longitudinal directions. Moreover, the face of the sample in contact with the grids was found to have grids in relief showing further evidence of close contact.

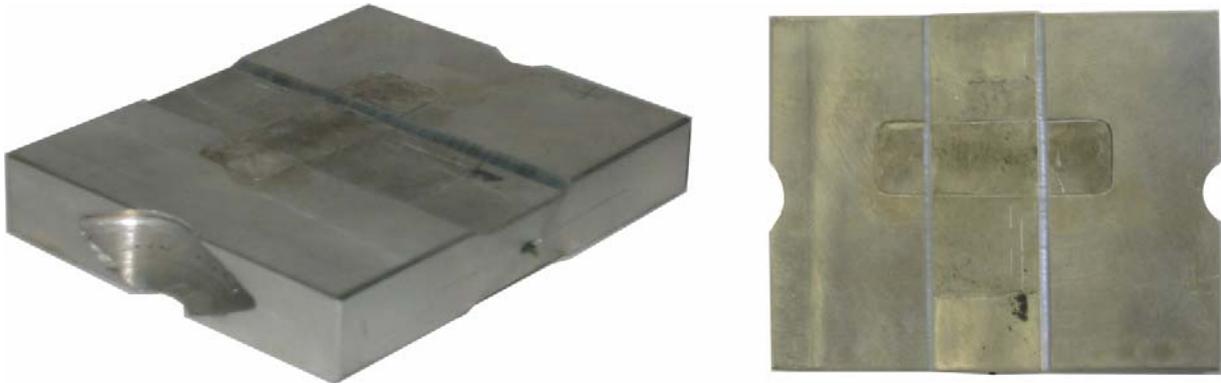


Figure 4 – Left: overview of the sample after the compression test. **Right:** top view of the sample. No detachment was observed between insert and work-piece in both transverse and longitudinal direction.

After being cooled down with compressed air, the specimen was carefully cut and the insert was extracted. Figure 5 shows the undeformed and deformed grid. The grid survived the test and the engraved lines can clearly be seen.

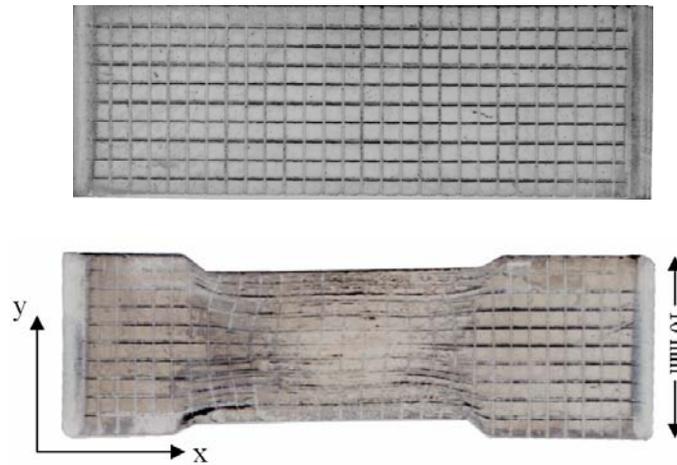


Figure 5 – Undeformed and deformed grid.

The components of the logarithmic strain were calculated by relating the coordinates of the vertices of each deformed element of the grid with the original square element. This was achieved with the aid of a Matlab[®] script^[10] that allowed automatic extraction of the coordinates from a scanned image of the deformed grid. Automatic recognition of the coordinates of the intersections was not possible given the difficulty of adjusting the brightness and contrast of the picture on the whole insert. For this reason, manual plotting with the computer mouse was finally chosen as the method for coordinate extraction. An assessment of the accuracy of this technique led to acceptable relative errors of up to 2.4 %^[10].

3. Finite Element Model

By making use of symmetry conditions one need model only a quarter of the sample. The model adequately simulated the real situation of both sample and insert for a total of

approximately 13,200 nodes (figure 6). The mesh was built using elements suitable for coupled thermo-mechanical analysis. The simulation took 19 hours CPU time on a Pentium IV 3.2 GHz processor equipped with 1 GB RAM memory. Due to the tools being at the same temperature as the sample, little heat exchange was expected. Hence the tools were not meshed and were considered as rigid bodies.

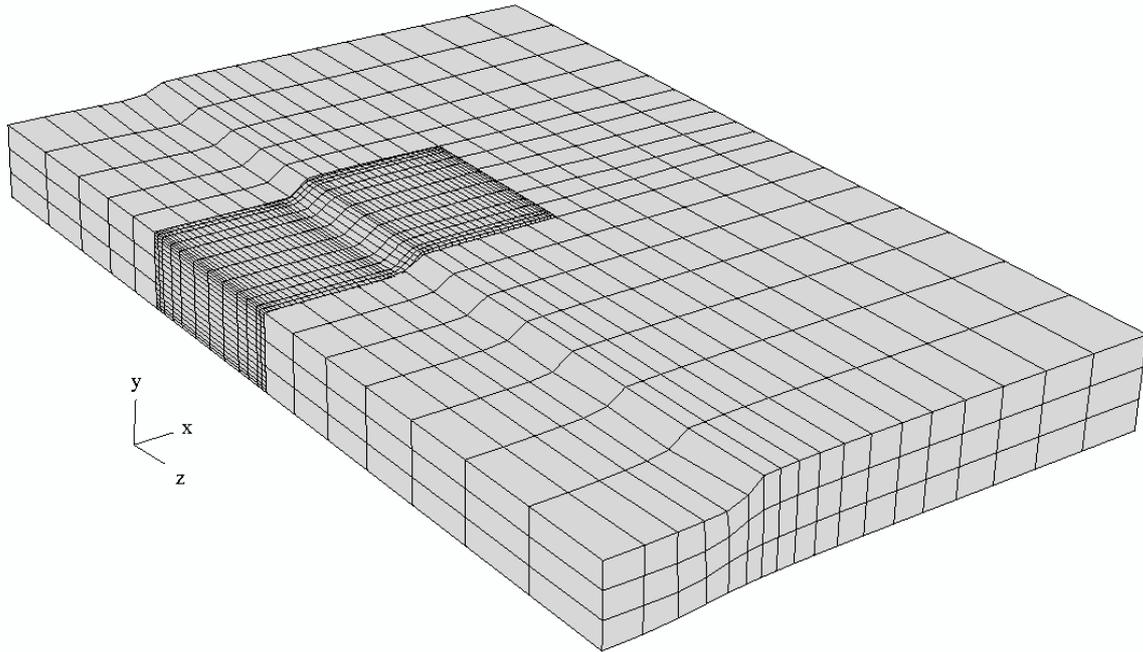


Figure 6 – 3D geometry and mesh. The mesh is refined in the insert and close to the contact area. Only a quarter of the geometry was modelled. The tool is not shown.

The finite element code used for this work (ABAQUS[®]/Standard 6.4) is an implicit commercial code that employs a standard Coulomb friction algorithm to model contact interactions, assuming that no relative motion occurs between the two surfaces if the shear stress across their interface is less than the critical stress defined as

$$\tau_{cr} = \mu P, \quad 1)$$

where μ is the coefficient of friction and P the contact pressure. The coefficient of friction between tools and sample (graphite lubricated) was measured by means of a Bowden & Leben type friction rig made available by the Tribology Group of the University of Sheffield. The resulting coefficient of friction was 0.1, value that has been used in other studies when modelling contact between aluminium and steel in compression tests when graphite is used as a lubricant.^[3] The unlubricated contact between insert and work-piece was modelled using a coefficient of friction of 0.5 in agreement with the current literature with reference to aluminium to aluminium dry contact.^[11]

3.1 Material

The material behaviour was modelled using an inverse hyperbolic sine function (f in equation 2), with parameters fitted to stress/strain data obtained through hot plane strain compression tests.^{[12][13]} This relationship models a viscoplastic behaviour linking the flow stress with temperature, strain and strain rate.

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T) \quad 2)$$

In this numerical model, the fraction of plastic work per unit volume dissipated as heat was assumed to be 95% ^[10] and 50% of the heat generated by friction was absorbed by the sample.

3.2 Constant strain rate and tool velocity

During a plane strain compression test with constant strain rate, the tool moves according to equation (3). In other words, at any given instant the ratio between the linear velocity of the tool v and the remaining thickness of the sample h has to be constant and equal to the applied strain rate.

$$\dot{\epsilon} = \frac{v}{h} \quad 3)$$

A FORTRAN[®] program was written to feed ABAQUS[®] with the correct velocity values during the compression.

3.3 2D and 3D models

A two-dimensional (2D) model was also built supposing plane strain conditions on the centre-plane of the sample. This condition implies that no deformation is expected along z-direction on the centre-plane of the sample. The aim of this model was to investigate whether a less demanding 2D model could be used instead of a 3D one to predict the strain components without loss of accuracy. Figure 7 shows the 2D geometry: symmetry conditions were used to model only a quarter of the whole geometry.

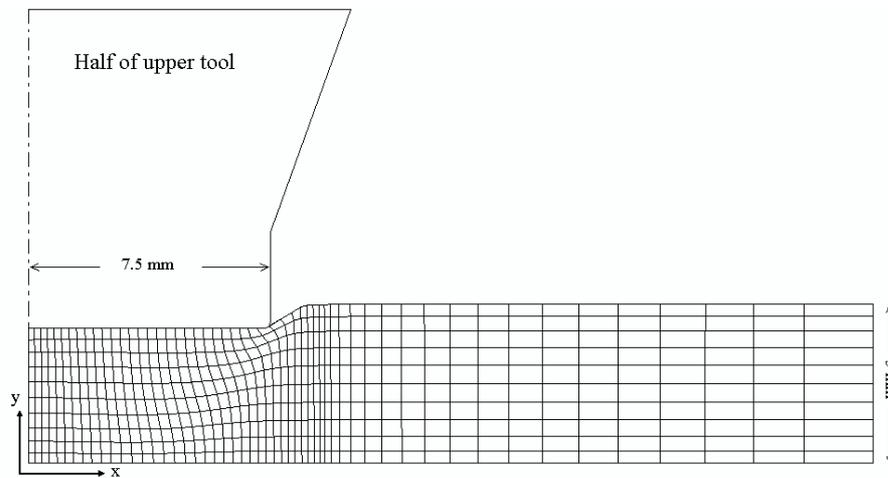


Figure 7 – 2D geometry and mesh. Due to symmetry, only a quarter of the full geometry was modelled.

4. Results

The temperature rise due to plastic deformation was measured during the test and compared with the numerical results extracted from an element at the same position as the head of the thermocouple. The experimental and numerical temperature profiles are shown in figure 8. No significant difference was found between the 2D and 3D temperature profiles.



Figure 8 – Experimental and numerical temperatures extracted from the sample and from the 2D FE model

The 3D numerical model allowed the evaluation of the gap (contact opening) between insert and work-piece. Figure 9 shows the amount of opening on the contact surface in the form of a contour plot. As can be seen, the maximum gap between insert and work-piece was 0.27 mm in a small area close to the surface. The gap occurred in an area where the tools are not in touch with the sample, suggesting that the friction between tool and sample/insert contributed to preventing detachment along the transverse direction. This phenomenon led to sticking contact conditions in the area where the strain was measured.

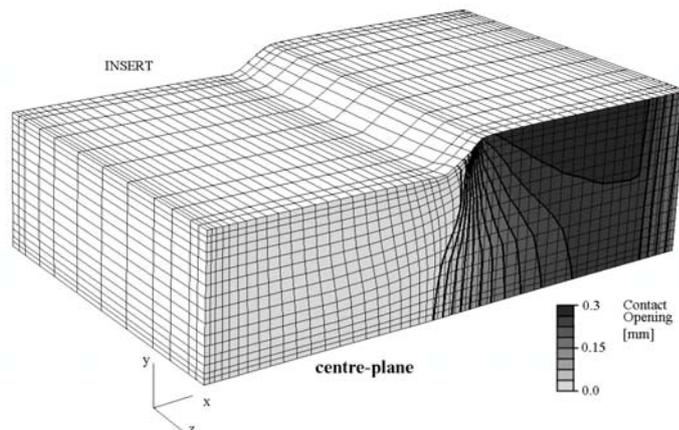


Figure 9 – Contact opening between work-piece and insert on the centre-plane.

The components of the logarithmic plastic strain were extracted from the 2D finite element models and compared with the measured ones. Figure 10 shows a comparison between finite element and experimental contour plots of the three components of the logarithmic plastic strain.

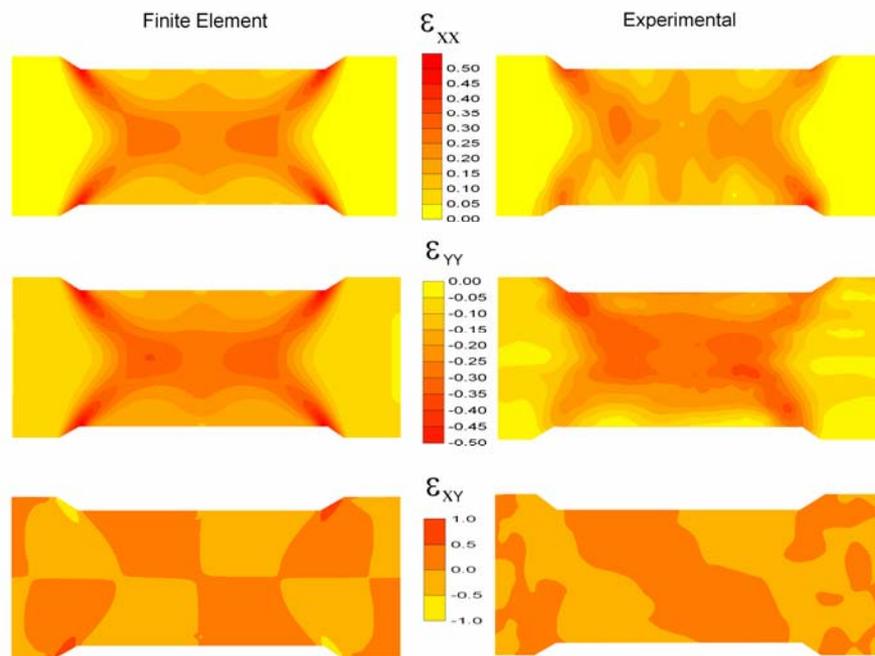


Figure 10 – Numerical (left) and experimental (right) contour plots of the components of the logarithmic plastic strain. The numerical values were obtained assuming perfect alignment between tools.

The comparison in figure 10 has been obtained by considering a model with no misalignment of the tools during the test. In fact, misalignment is common in a compression test: in the case of the insert where the data in figure 10 was extracted, an offset of about 1 mm was measured between the two tools, the upper tools being shifted towards the right. Figure 11 shows that, by considering a model with realistic amount of misalignment, the match between numerical and experimental plots improves considerably. A very similar deformation field was observed considering a slight rotation of the upper tool.

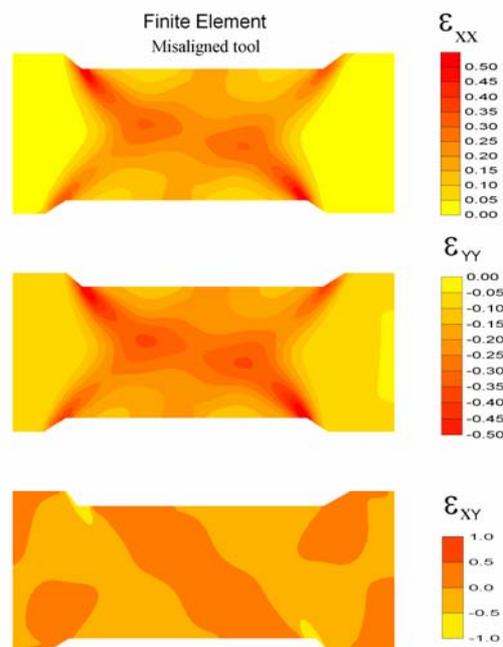


Figure 11 – Numerical contour plots of the components of the logarithmic plastic strain considering a misalignment of 1 mm between tools (top tool shifted to the right).

The elements on the centre-line of the insert were analysed separately in order to highlight the differences between 2D and 3D models (fig. 12). The 2D and 3D plastic strain were both extracted from the centroid of the elements. A difference of 15% was found between the maximum values of the xx components whereas less than 8% difference was found for the yy component in this particular area of the insert.

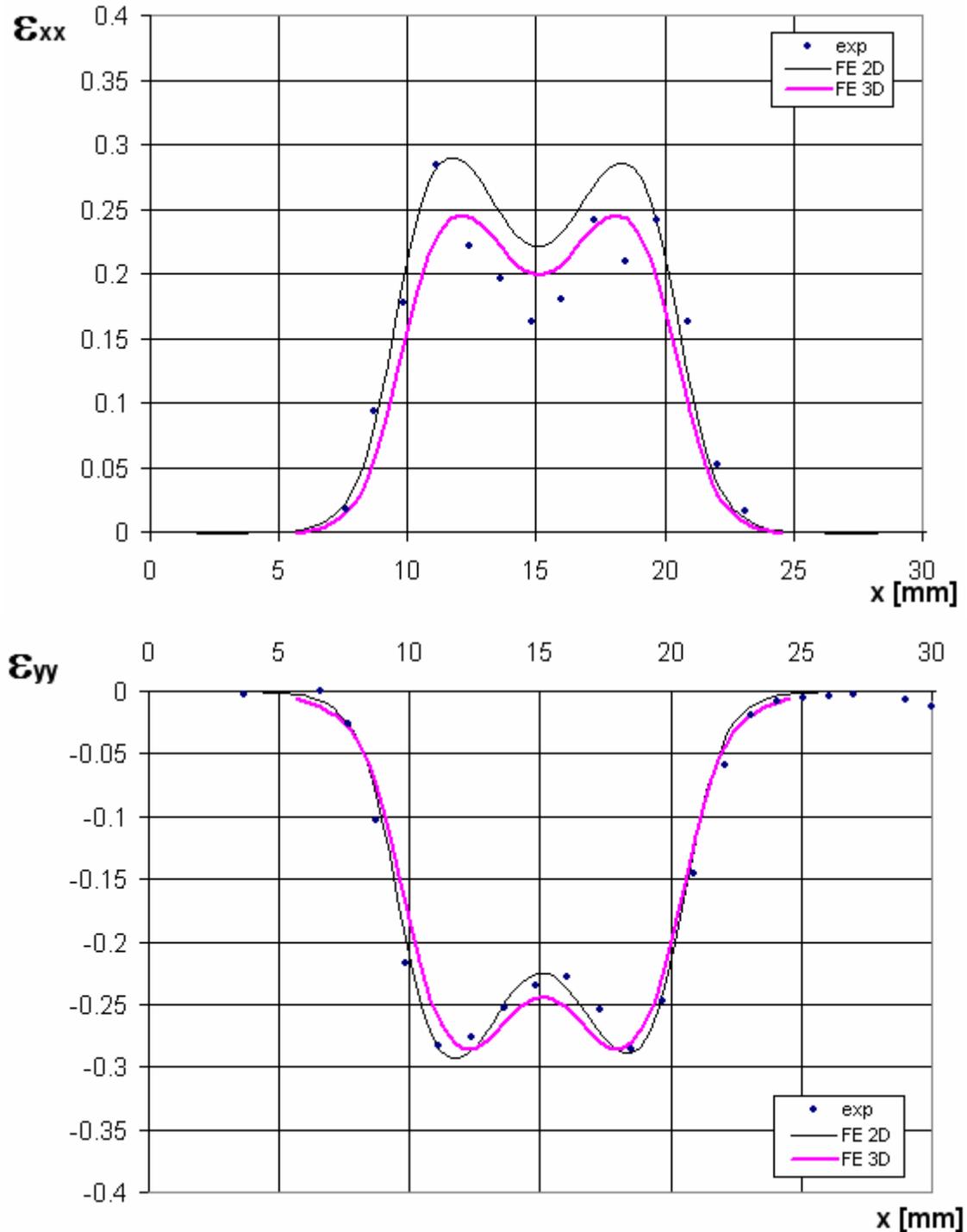


Figure 12 – Comparison between the components of the logarithmic plastic strain calculated by the code (2D and 3D model with aligned tools) and measured on the insert (dots) for a row of elements along the centre-line.

This difference can be explained by considering figure 13 where the zz component of the plastic strain is shown after being extracted from the 3D model. The strain along the z direction reaches a maximum where the maximum difference between 2D and 3D is observed. This suggested that the plane strain condition for this geometry was not fully achieved on the centre-plane.

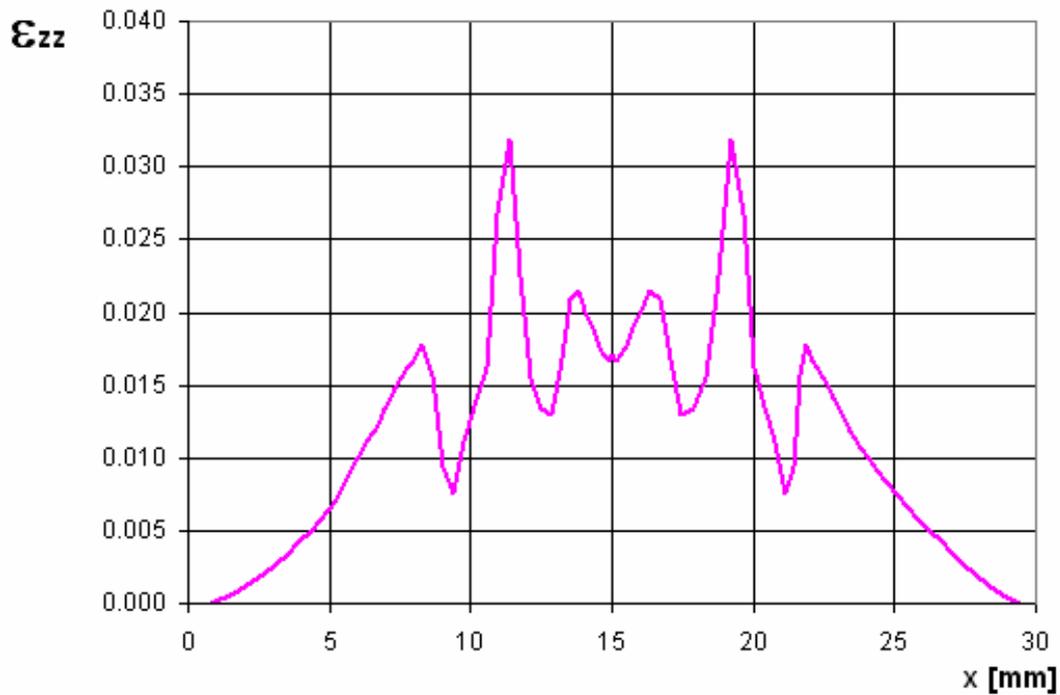


Figure 13 – zz component of the logarithmic plastic strain extracted from the 3D model in the same area as the one considered in fig. 13 (Note the different scale on the ordinate axis).

5. Discussion

The observed lack of detachment, confirmed by the numerical model, proved that close contact was achieved between insert and work-piece during the test. Moreover, the fact that a grid was found on the surface of the slot facing the gridded face of the insert was further evidence of negligible relative motion between insert and work-piece. Other engraving techniques, such as photo-etching, are being considered in order to reduce the width of the grid. Nevertheless the necessity for thinner grid-lines must take into account the need for a strong grid capable of undergoing large deformations at high temperatures.

Accurate prediction of the deformation in the central area of the sample implies that the components of the strain obtained by FE modelling can be used in microstructural studies with confidence. This is important when dealing with texture studies since differences between measured and predicted textures can be attributed to the texture model itself rather than to the input data. To address this issue, the FE model used in this work was checked against the experimental data. The measured components of the logarithmic plastic strain were found to be in good agreement with the numerical values when considering a slight misalignment of the tools. However, due to the relatively large grid pitch, the measurement of the strain was more accurate in the central area of the insert rather than closer to the tools where steep gradients of deformation were found. This issue could be overcome by using different techniques that allow the creation of a grid with a smaller pitch such as micro-lithography techniques ^[15].

As can be seen in figures 10 and 12, the deformation was not uniform along the centre-line of the insert and the maximum deformation was not achieved at half the length of the insert but about 3 mm away on both sides. This non-uniformity of the strain translates into a substantial difference between the applied strain (0.22) and the local strain in the proximity of the centre

of the insert. If we consider the centre-line, this leads to variations of the computed ϵ_{xx} of up to 20% within a distance of 3 mm from the centre.

The measured temperature profile was very close to the predicted one. This is very important considering that the flow stress is directly linked to the temperature and the code selects a particular value of the stress-strain curve at any time depending on the current temperature according to equation (2).

The comparison between the 2D and 3D model on the centre-line showed that the 3D model was slightly more accurate than the 2D one in predicting the strain. The presence of some deformation along the transverse direction suggested that the plane-strain assumption in the 2D model is not fully valid but can still be accepted depending on the desired accuracy. Moreover a wider sample would probably assure plane strain conditions on the centre-plane.

6. Conclusions

An insert with an engraved grid was used to measure the deformation in a plane strain compression test. The grid survived the test and could be analyzed to calculate the strain. No separation was observed between insert and work-piece.

Good agreement was found between experimental and numerical strain in the central area of the insert, whereas a smaller pitch is required to appreciate the sharp deformation gradient in the areas close to the edge of the tools. Better quantitative agreement might probably result from the use of grids created by more accurate methods such as photo-etching or micro-lithography. However, these alternative techniques have to be tested in order to assess their strength and resistance to the test.

The components of the plastic strain were extracted and plotted for the whole centre-plane of the insert, showing a non-uniform distribution and considerable variations of the deformation in the central area of the insert, with values of the strain significantly different from the applied strain.

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