Experimental measurement of the deformation in hot rolling of aluminium 1% Mn: the grid technique

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Abstract
The *grid technique* is an experimental method for measuring the deformation in hot rolling. An AA3004 sample -fitted with an insert - was rolled in a single hot rolling pass at 400 °C. The insert was hand engraved with a *1x1 mm* grid and the analysis of the image of the deformed grid enabled the calculation of the components of the deformation gradient tensor. In order to prevent relative motion between the insert and the work-piece, four steel pins were used; after the test no detachment was observed between insert and sample. The temperature was monitored during rolling using two embedded thermocouples, one close to the surface and the other on the centre-line of the slab. The commercial finite element (FE) code ABAQUS was used to build a three-dimensional model of the rolling process. The recorded temperature was compared with the FE values evaluated after tuning the heat transfer coefficient. The FE model was run several times with different friction coefficients and the deformation gradient checked against the experimental measurement of the deformed grid in order to obtain the optimum friction coefficient. The experimentally determined deformation gradient and the measured temperature agreed well with the numerical values.

Introduction

The prediction of the deformation of hot worked aluminium is very important to the metal industry. Processes such as hot rolling produce significant microstructural differences through the thickness of the rolled material. This heterogeneous deformation leads to different deformation textures between the surface and the centre of the slab [1]. The mechanical properties of the final product depend strongly on the preferred orientation of the crystal grains (*texture*) due to the rolling process. Industrial defects such as *earing* (fig. 1) in a cup which has been deep-drawn from a rolled sheet are consequences of this problem [2,3]. Modern models for the texture prediction require, as input, values for the components of the *deformation gradient tensor* [4]. The deformation gradient tensor is invariably extracted from finite element (FE) models of the rolling process. However, FE models are sensitive to the parameters controlling friction and heat transfer between work-piece and rolls, and require experimental validation. The validation of the FE model implies the experimental measurement of the deformation gradient in the rolling process. This is not an easy task due to the very nature of the process; high temperature and deformation, friction and the speed of the process itself make the application of conventional measurement techniques impracticable.

Figure 1 – 'Earing' of a cup after deep-drawing from a rolled sheet of aluminium (source http://aluminium.matter.org.uk)

The aim of this work was to measure both the temperature and the deformation gradient in samples of a commercial aluminium alloy rolled in a laboratory mill under conditions that closely represented a breakdown rolling pass in an industrial process. A gridded insert was used to measure the deformation through the thickness of the slab, giving a reliable measurement of the deformation gradient after rolling. The commercial finite-element code ABAQUS/Standard ver. 6.4 was used to model the rolling process and the numerical data was compared to the experimental measurements in order to validate the code.

Rolling Experiment

The tests were carried out using a 50-ton laboratory mill with 68 *mm* diameter steel rollers and a furnace. The sample was centrally slotted in order to embed the insert which had been hand-engraved with a 1x1*mm* grid (fig.2) using a height gauge equipped with a carbide tipped scriber. The back of the specimen (left-hand end of the specimen in fig.2) was machined in order to make it easier for the operator to remove it from the furnace. The front of the sample was cut with an angle of about 20° to help the rolls drag the sample in the initial phase of the rolling. Two type-K thermocouples were fitted in two holes, one in the centreline, the other *3 mm* under the surface. The head of the thermocouples were in contact with the gridded insert on the centre-plane of the sample. In order to avoid relative motion between sample and insert, the latter was secured against the sample by four through-width steel pins (fig. 2).

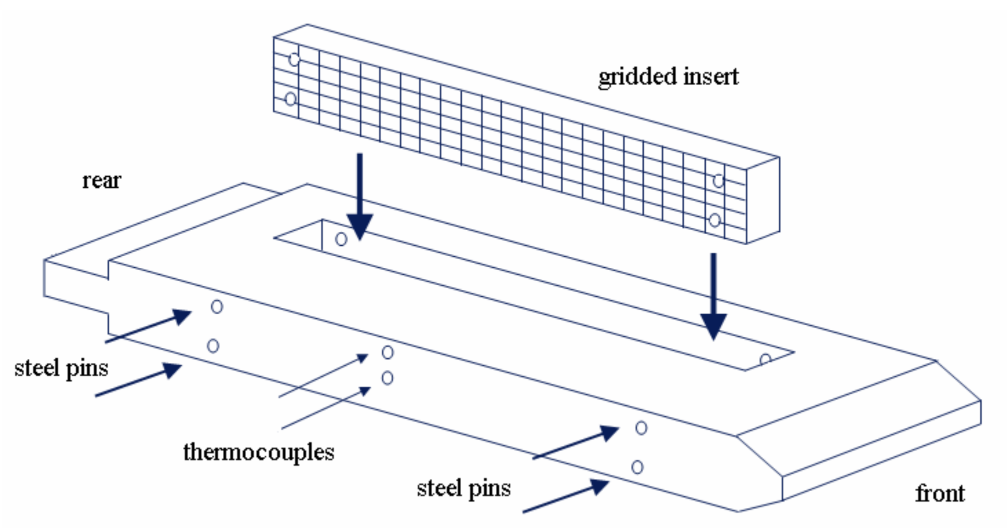

Figure 2 – View of the specimen and gridded insert.
The sample was 120 *mm* long, 60 *mm* wide and 20 *mm* thick. The insert was 10 *mm* wide.

The material used was a commercial alloy (AA3004) normally used for the body of beverage cans and it is produced through a complex rolling process.
The temperature in the furnace was set at 400°C and the sample was left in the furnace for two hours in order to achieve a homogeneous temperature. The sample was rolled in a single pass with 50% reduction at 11 revolutions per minute, and then quenched in water. After the test, no gap was observed between the insert and the specimen (fig. 3), confirming the effectiveness of the pins in ensuring close contact under high deformation. After being quenched, the sample was opened up by carefully cutting longitudinally and the insert was extracted. The face of the sample in contact with the grids was found to have grids in relief as well, showing further evidence of close contact during rolling.

Moreover the specimen after rolling was relatively straight indicating a successful rolling procedure.
Figure 3 shows a picture of the grid after rolling. The engraved lines can clearly be seen although the width of the lines is significant compared with the pitch.

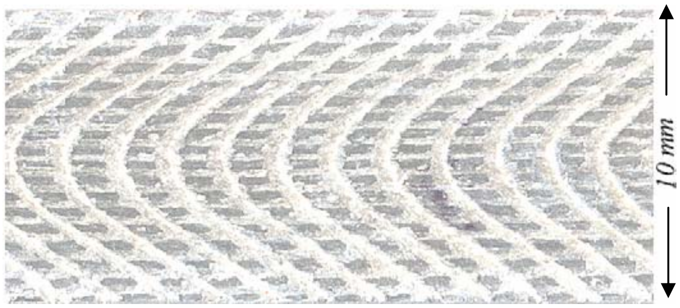

Figure 3 – Deformed grid after rolling. The width of the lines is significant compared to the pitch.

Deformation Gradient Tensor: definition and calculation

The deformation gradient tensor, which contains information about both the deformation and the rotation of the element, relates the initial and final states in a linear way (fig. 4).

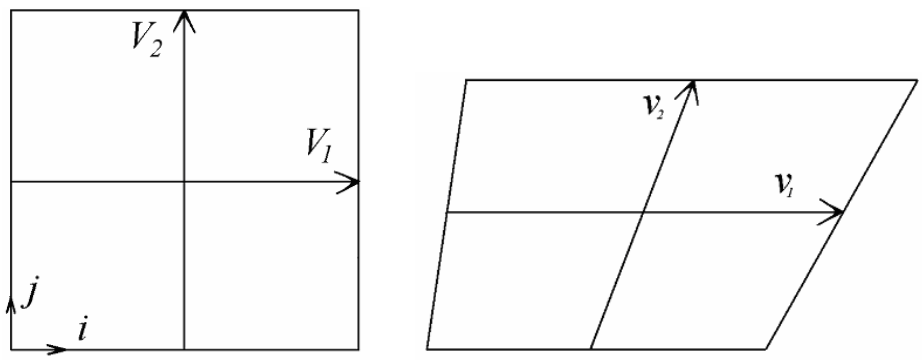

Figure 4 – Square before deformation (left) and after deformation (right).

$\boldsymbol{V_1}$ and $\boldsymbol{V_2}$ ($\boldsymbol{v_1}$ and $\boldsymbol{v_2}$) in figure 4 are the two vectors that link the middle of the opposite sides of a given square, in the undeformed (deformed) configuration. They are defined as follows:

$\boldsymbol{V_1}=A\boldsymbol{i}+B\boldsymbol{j}$,
$\boldsymbol{V_2}=C\boldsymbol{i}+D\boldsymbol{j}$,

and the corresponding deformed vectors

$\boldsymbol{v_1}=a\boldsymbol{i}+b\boldsymbol{j}$,
$\boldsymbol{v_2}=c\boldsymbol{i}+d\boldsymbol{j}$.

The deformation gradient tensor F was calculated at the *centroid* of each element, using equation 1.

$$\begin{bmatrix} a & c \\ b & d \end{bmatrix} = F \cdot \begin{bmatrix} A & C \\ B & D \end{bmatrix} \quad \Rightarrow \quad F = \begin{bmatrix} a & c \\ b & d \end{bmatrix}\begin{bmatrix} A & C \\ B & D \end{bmatrix}^{-1}. \qquad (1)$$

A MATLAB script was written to automate the coordinate extraction from an image of the deformed grid after the intersections between vertical and horizontal lines had been manually marked. Confidence in the reliability of this technique depended first upon estimating its accuracy. Accuracy in manual plotting was first assessed by applying the script to a drawing of a perfect black square over a white background. The final deformation gradient tensor should, in theory, equal the identity tensor for an accurate method. The optimum contrast and the very thin lines led to a relative error that was less than 0.2%, this low value being obtained using a zoom function that helped increase the plotting accuracy. The assessment of plotting accuracy was then applied to a real engraved grid. The lower quality of the picture contrast together with the non-uniform width of the grooves made the plotting more difficult to perform. When clicking on grid intersections, the inaccuracy increases as the ratio of the groove width to the pitch size increases. Therefore the error had to be estimated for each component of the tensor F, using an engraved grid that featured pitches close to those of experimentally deformed grids. After this analysis, the statistical error was estimated from the standard deviation of the calculated values. The final error could be reduced by averaging (over sets of five grid elements) the calculations along a material streamline. This led to very acceptable statistical errors; the relative error associated with the yx component was 8 %, the one associated with F_{yy} was 2.4 % and the one associated with F_{xx} and F_{xy} was less than 1%.

Finite Element Model

The commercial code ABAQUS/Standard ver. 6.4 was used to build the numerical model. The 3D model of the stock and roll (fig. 5) took advantage of the symmetry condition along plane XY and plane XZ so that only half of a roll and a quarter of the slab were considered. Both the roll and stock geometries reproduced the rolling mill used for the test and the specimen used for the tests.

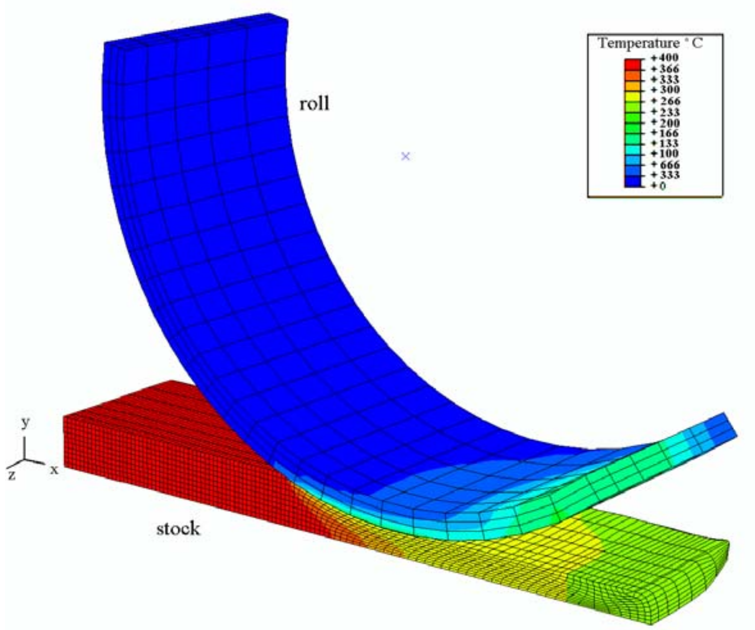

Figure 5 – Finite element geometry and mesh. Temperature contour plot at half the rolling pass.

The model consisted of 10,000 nodes and the elements were suitable for coupled thermal-stress analysis. The *heat transfer coefficient* (HTC) between roll and stock used in the model was tuned in order to have the best match between experimental and numerical temperature curves (fig. 7). Also the friction coefficient was modified to obtain the best agreement between experimental and numerical deformation gradients. The optimum HTC was found to be 55 $kW/(m^2K)$ and the final friction coefficient was 0.6. A comparison between the FE mesh obtained with this value of the friction coefficient and the deformed grid is shown in fig. 6.

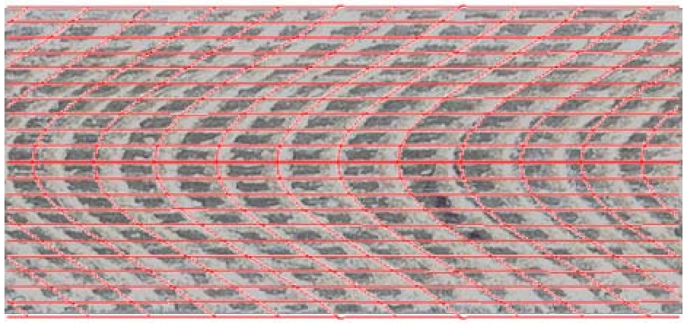

Figure 6 – Finite element mesh superimposed on the deformed grid.

The computer used to run the model was equipped with a Pentium IV 3.2 GHz processor and 1 GB RAM memory. The time needed to simulate the complete rolling of the whole 120 *mm* long stock was 140 hours.

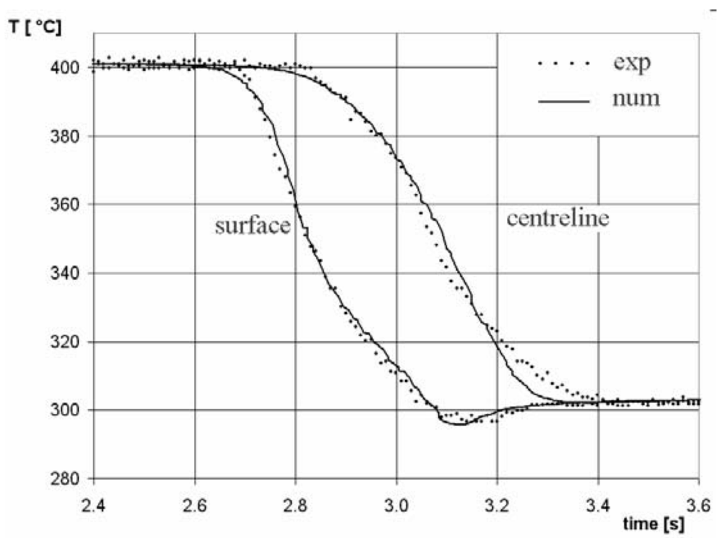

Figure 7– Comparison between numerical (continuous lines) and experimental (dots) temperature profiles for the surface (left) and the centreline (right).

A comparison between numerical and measured deformation gradients is shown in Figure 8.

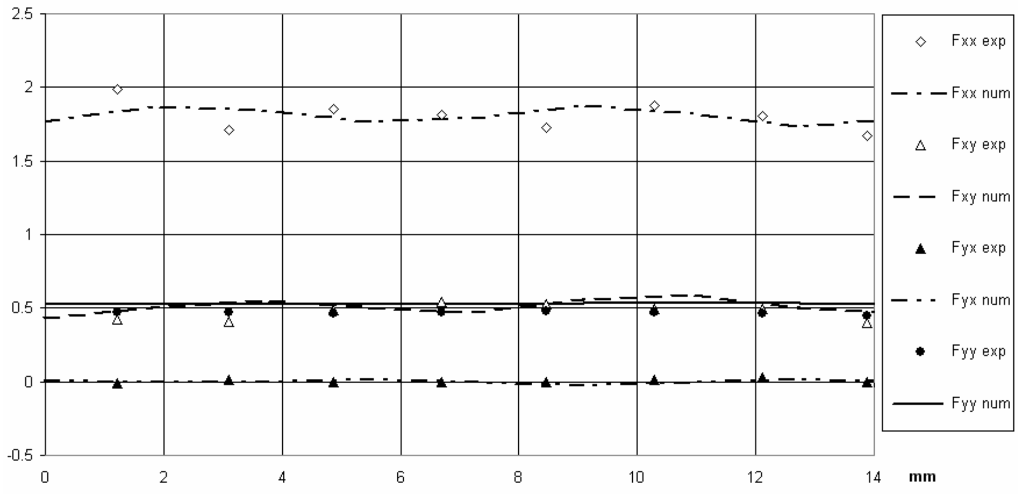

Figure 8 – Deformation gradients measured in the top row of elements of the grid (the row closer to the surface).

The comparison between numerical and experimental data shown in figure 8 is good, particularly considering the potential errors associated with the engraving method.

Discussion and Conclusions

This paper has shown a way of measuring the deformation gradient in a 50% reduction hot rolling pass. The grid was still visible after the pass despite the high deformation, and no detachment was observed between the insert and the rest of the sample hence separation was successfully eliminated by the steel pins.

The deformation gradients were measured and an accuracy analysis was carried out to evaluate the error associated with the grid technique. Given the importance of the deformation gradients for texture prediction, a rigorous method was developed to extract them automatically from a picture of the deformed grid. The grid technique proved to be reliable for an experimental evaluation of the deformation gradient but various sources of error were found in the procedure itself mostly due to the width of the engraved lines and the manual nature of the procedure. However, the need for thinner grid-lines must take into account the necessity for a strong grid that would survive large deformations at high temperatures. The grid technique provided a true measurement of the deformation gradients through the thickness of the slab. This cannot be achieved using conventional experimental techniques. The numerical model has been validated using this experimental data. Tuning the *friction coefficient* and the *heat transfer coefficient* was necessary to match experimental and numerical temperature profiles and the final results showed a very good match between predicted and measured data.

The accurate prediction of the through-thickness deformation gradients provided by the numerical model means that the components of the deformation gradient tensor can be used in texture prediction programs with confidence.

References

[1] U.F. Kocks, C.N. Tome', H.-R. Wenk, *Texture and Anisotropy*, Cambridge University Press
[2] E. M. Mielnik, *Metalworking science and engineering*, McGraw-Hill
[3] George E. Dieter, *Mechanical Metallurgy*, McGraw-Hill
[4] Y. Basar, D. Weichert, *Nonlinear continuum mechanics of solids*, Springer, 2000.