Prediction of extruded microstructures using experimental and numerical modelling techniques

C. Harris, Q. Li, M. R. Jolly

Aluminium is a valuable material with an ever-expanding amount of uses. However, as the use of aluminium increases so do the demands on its properties – both mechanical and physical. After the casting of a specific alloy the only method of altering the microstructure and consequently the properties of that alloy is by thermomechanical processing.
In some cases extruders require a particular final microstructure in order to attain specific mechanical properties for product safety reasons, for example in structural applications. In others the resulting, although undesired, microstructure is an almost accepted part of the process, for example peripheral coarse grain in the extrusion of hard alloys. In this study, the formation of the final extruded microstructure was investigated as a function of the strains, strain rates and temperatures produced in the aluminium extrusion process. The strains, strain rates and temperatures are themselves a function of a particular extrusion die design and process control. The investigations were carried out using a combination of industrially extruded metal, laboratory scale experimentation and Finite Element Modelling of the whole extrusion process.
This paper will introduce the current findings on the development of fundamental techniques that can be used within industry to predict the microstructures of extruded products. The ultimate aim is that the same techniques can then be used to specify extrusion die design and process control parameters in order to accurately produce the required extruded microstructures.

Parole chiave: aluminum, extrusion, phisical metallurgy

INTRODUCTION

As the potential structural, automotive and aerospace applications of aluminium extrusions expands so does the need to improve their mechanical and physical properties. These properties are largely determined by the final microstructure of the product and so it is imperative to evaluate how extruded microstructures evolve so that not only can properties be predicted but they can also be designed.
However, extrusion is a complex forming process with many process parameters such as billet composition, varying extrusion die geometries for the same profile, ram speeds, temperatures and post forming heat treatments [1]. Traditional approaches to process development have involved commercial plant trials, which are costly and disruptive to business, or laboratory scale trials, which can be prone to errors when scaling up to full size production facilities. However with the rapid and continual advances in hardware and software the use of computational techniques, such as finite element modelling, to accurately simulate full metal forming processes such as rolling, extrusion and forging is now widespread [2-4].
There is a growing trend in marrying the above analytical techniques together whereby field variables are extracted from an initial commercial scale extrusion run and the resulting extruded microstructure examined [3-4]. These field variables can then be input into a finite element model and the whole extrusion run simulated. Variables such as strain, strain rates and internal billet temperatures (which are extremely difficult to measure on a commercial scale) can then be extracted from the simulation results and these in turn can be used within established microstructural models. The result is that through reverse engineering we then have the ability to determine what the extrusion process parameters *should be* in order to produce the ideal microstructures required. The last step in this process can be carried out by running further finite element simulations, with no costly commercial trials needed.
This paper will deliver preliminary results which demonstrate the use of finite element modelling, laboratory scale experimental work and industrial trials as techniques which, when combined, can effectively be used as tools to solve real problems within the extrusion industry.

Chris Harris, Qiang Li, Mark. R. Jolly
IRC in Materials, University of Birmingham, Edgbaston Birmingham, B15 2TT, UK

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BACKGROUND TO THE PRESENT STUDY

The case study used to investigate the effectiveness of finite element modelling in the simulation of the extrusion process and subsequent microstructural prediction was the formation of peripheral coarse grain (PCG) in a 2014A aluminium alloy. Peripheral coarse grain is a well-documented phenomenon occurring in some 2xxx, 6xxx and 7xxx series alloys [1,5,6-9] and is a coarse grained layer of recrystallised material occurring in the outer band of an extruded cross section. 2014A is a popular 2xxx series alloy extrusion used in the aerospace industry exhibiting high strength combined with good corrosion resistance, ductility and toughness. PCG is detrimental to these qualities and it is for these reasons that it is desirable to minimise or even eliminate the PCG layer [9]. In 2014 it is acknowledged [1,5] that PCG occurs as static

recrystallisation during the solution heat treatment after extrusion. The extrudate does not recrystallise during the extrusion process since exit temperatures are mostly kept below 480-490ºC in order to avoid surface deterioration. The solvus temperature in 2014A is ~500ºC and the solidus temperature is ~510ºC creating a small window for the effective solution heat treatment at ~505ºC [5]. As the solution heat treatment temperature has to be so high recrystallisation and grain growth after extrusion are *almost* inevitable (although grain growth is limited somewhat by the transition elements Mn, Cr and Zr within the alloy) [1].
Thus in order to restrict the formation of PCG within 2014A one has to identify the process conditions under which the recrystallisation temperature is below the solution heat treatment temperature and then try to alter the process conditions and raise the recrystallisation temperature to above the solution heat treatment temperature i.e. generate a microstructure that is more stable and resistant to recrystallisation during solution heat treatment.
For a given alloy composition, a specific homogenisation prior to extrusion and solution heat treatment post extrusion it is the thermo-mechanical processing of the billet occurring during extrusion that ultimately determines at what temperature the extrudate will recrystallise. More specifically, the microstructural evolution will be dependant upon the deformation temperature (T), the strain (ε) and the strain rate ($\dot{\varepsilon}$) [2]. The strain rate and deformation temperature are often incorporated into a single parameter – the Zener-Holloman parameter (Z) – which is defined as:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \qquad \text{Eqn. (1)}$$

Where ‘Q’ is the activation energy for deformation (144408 $Jmol^{-1}$ for 2014 [10]), ‘R’ is the universal gas constant (8.3144 $Jmol^{-1}K^{-1}$) and ‘T’ (K) is the absolute temperature. This parameter has been shown to be adequate when describing material behaviour during the extrusion process [10]. The Zener-Holloman parameter is closely related to the flow stress and hence the dislocation density of a worked sample which in turn is a measure of the stored energy within a material after deformation. Generally speaking material deformed at high strains combined with low temperatures and/or high strain rates (i.e. large Zener-Holloman parameter) will recrystallise at a lower temperature than material deformed at lower strains combined with higher temperatures and/or lower strain rates.
For the purpose of this study we needed to find out the critical conditions under which PCG formed and then through altering the extrusion process parameters increase the recrystallisation temperature so that the material does not form PCG after solution heat treatment. It is important to note that throughout this study the billet composition, homogenisation treatment and solution heat treatment were all fixed and/or optimised. This is not considered an unrealistic scenario when compared to commercial practices.

EXPERIMENTAL DETAILS

Commercial scale production run details

The commercial scale extrusion run was carried out using 2014A billet cast within the standard compositional limits shown below [Table 1]:

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.5-0.9	0.7	3.9-5.0	0.4-1.2	0.2-0.8	0.1	0.25	0.15

Table 1: Compositional limits of 2014A – Element wt. % - Balance - Al

Figure 1: Macro-etched slice from flat die extruded bar

Figura 1: Sezione macro-attaccata di una barra piatta estrusa

The billet underwent a standard homogenisation at 490ºC for 4hours. The billet was 406mm in diameter and 550mm in length. The extrusion die was a standard flat-faced die designed for extruding bar 101mm in diameter. The run was carried out on a 5000T direct extrusion press with an initial die temperature of 395ºC, billet temperature of 430ºC and container temperature of 400°C. The ram speed was 2.32mm/s (extrusion speed of 2.44m/min) and the discard was 90mm. Material was taken 5m from the front end to be analysed after a standard solution heat treatment at 505ºC. A die designed to eliminate PCG was also run under similar conditions [Die X] and material taken from the same point in the extrusion. Details regarding this die are limited due to the commercially sensitive nature of the information.

Finite element modelling details

The whole extrusion process was modelled on a 1:1 scale using the commercial metal forming code DEFORM2D, details of which can be found in [11]. All the details recorded from the first trial were used as the boundary conditions as well as other standard data for heat transfer etc. A friction coefficient of 0.6 was used for any billet/die or billet/container contact. A die designed to eliminate PCG was also modelled [Die X] although, as above, the exact process conditions cannot be discussed in this paper due to commercial sensitivity. The simulations were carried out using a Silicon Graphic Origin 200 with 4 R10000 processors and 0.5Gb of RAM. Rigid viscoplastic materials data for the 2014A alloy used was inputted for the FEM simulations, obtained from compression experiments carried out on a Gleeble 3500 thermomechanical testing machine. After the simulations were completed ‘point tracking’ was carried out which enabled the extraction of strain, strain rate and temperature data at any required points in the extrusion.

Laboratory scale examination details

A disc cut from the commercial production run of each die (flat and Die X) was ground and macroetched in a caustic solution in order to reveal any PCG. These discs were also sectioned and prepared for optical microscopy using standard metallographic techniques for aluminium including etching in Barkers reagent in order to reveal the microstructure.

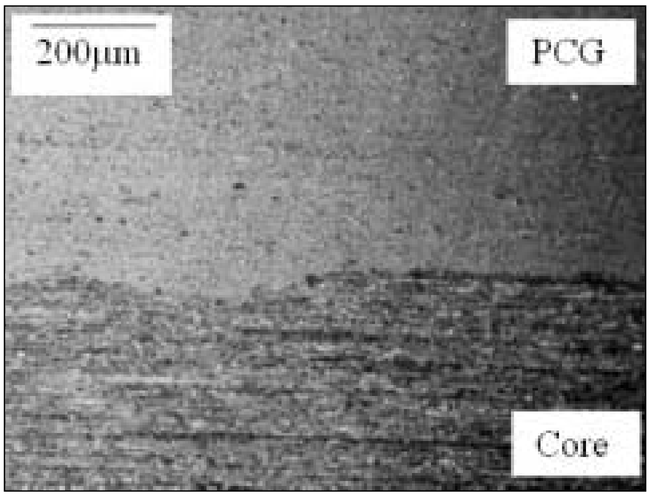

Figure 2: Optical micrograph showing the PCG boundary

Figura 2: Micrografia ottica che mostra i bordi PCG

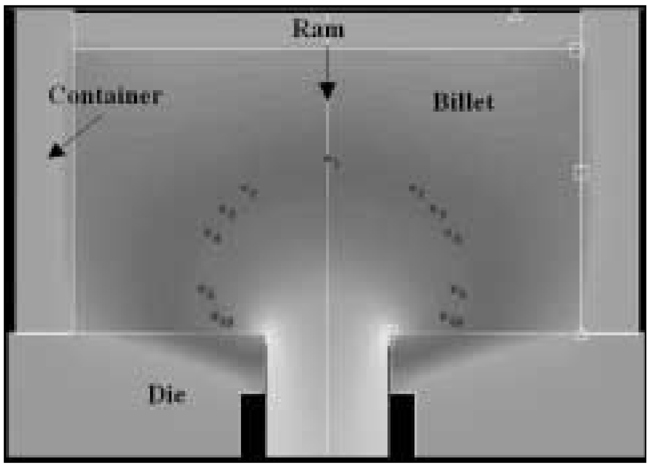

Figure 3: A snapshot showing the configuration of the finite element model with the start point of the point tracking.

Figura 3: Immagine che mostra la configurazione del modello ad elementi finiti con il punto iniziale in corrispondenza dell'allineamento del punto

RESULTS AND DISCUSSION

Figure 1 is a slice of the 101mm bar extruded through the flat die, taken at 5m from the front end. This is typical of what was expected with the PCG clearly evident around the periphery of the bar separated by a sharply defined boundary from the unrecrystallised inner core. The coarse grains form an almost perfectly concentric band with an average width of ~4mm.

This bar was then sectioned further so that more accurate measurements of the PCG layer could be taken at a higher resolution using optical microscopy.

Figure 2 is an optical micrograph which shows the sharp PCG boundary running across the centre of the micrograph. Above the boundary is part of a single recrystallised grain and below the boundary is the fibrous core of material where the extrusion direction can still be identified. Obviously being so close to the boundary one would expect the 'core' to be partially recrystallised, as reported in another study [7] however it is impossible to tell this from an optical micrograph and would need further examination using another technique e.g. electron backscatter diffraction which would detail the grain boundaries. For the purpose of this study the PCG boundary is taken as the point where the process conditions during extrusion have determined where the material recrystallises. Using the optical microscope a more accurate measurement of the depth of PCG could be taken and was found to be 3.15mm ± 0.15mm.

The depth of the PCG layer was then used in determining where the point tracking would be run in the finite element simulation. The finite element model was first run so that the complete billet (excluding the discard) was extruded. Ten points were placed at 5m at various depths within the extrusion and the extrusion was then in effect reversed so that it was possible to see where the points started from in the billet. For clarity only six of these points can be seen in Figure 3 which also shows the configuration used for the model.

The colours in the picture represent temperature with blue being 'cold' and yellow being 'hot'. As is expected the hottest points are at the bearing surface. As the points track through the simulation the temperature data is extracted at each step so at each step an instantaneous value for temperature, strain and strain rate is obtained, building up a process history for each point as it travels through the die. Although data for all 10 points was collected the most important points are point 10 (which is on the surface of the extrusion), point 5 (which is at the PCG boundary 3mm below the surface) and point 1 (which is in the centre of the extruded bar). This enables a comparison of the two extremes at the centre and surface of the bar to be made as well as the information at the PCG boundary.

Interestingly, although the points start in the semi-circular pattern illustrated in Figure 3 they all finish parallel at 5m. This demonstrates the different material velocities within the billet with the material flowing faster at the centre of the billet than near to the dead metal zone. This helps justify that the model is behaving as is expected in the real process.

Figures 4 and 5 are the resulting graphs from the point tracking data, both shown as a function of the ram displacement. In figure 4 the Zener-Holloman parameter is shown as calculated using the strain rate and temperatures as well as the constants shown in Equation 1. In figure 5 the effective strain history can be seen as the points travel through the die and past the bearings.

In order to have confidence in the modelling results it is necessary to justify them with 'real' values. Unfortunately the only parameter obtainable from the commercial production run was the exit temperature of the bar, which was measured to be 490ºC at 5m. The modelling calculated the exit temperature to be 473ºC, which is a 3.5% difference. This discrepancy is only minor and can possibly be attributed to the friction coefficient used or an inaccurate heat transfer coefficient. Also, theoretically, the average strain in the die is calculated to be 2.86 (simply the natural log of the extrusion ra-

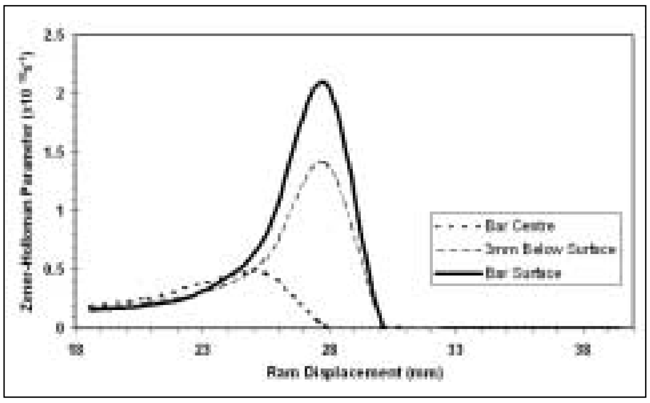

Figure 4: The Zener-Holloman parameter for three of the points tracked through the die

Figura 4: Il parametro Zener-Holloman per tre dei punti seguiti attraverso lo stampo

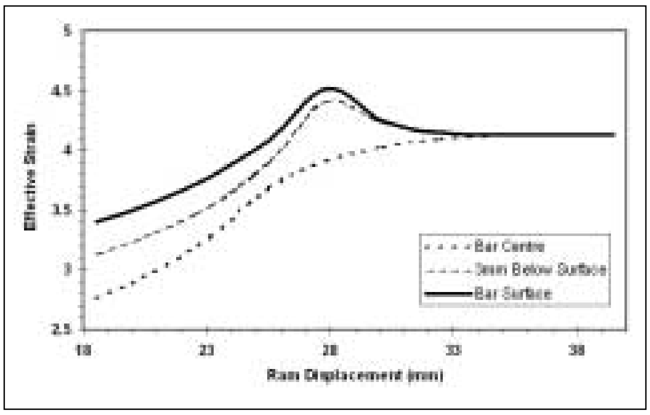

Figure 5: Effective strain for three of the points tracked through the die

Figure 5: Tensione effettiva per tre dei punti seguiti attraverso lo stampo

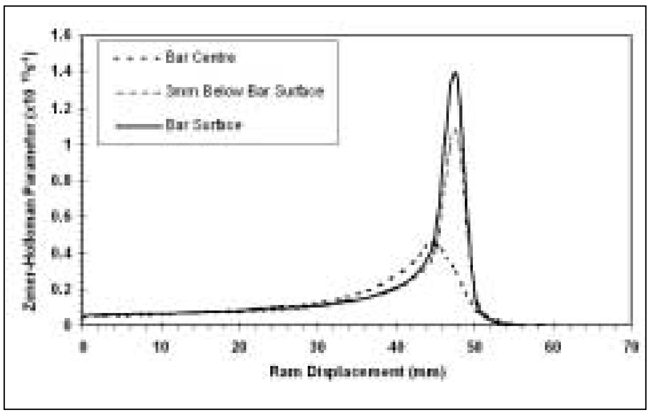

Figure 6: Zener-Holloman Parameter for Die X

Figure 6: parametri Zener-Holloman per stampo X

tio). From the point tracking data if the effective strain is averaged over all of the10 tracked points throughout the extrusion process the average effective strain calculates as 3.25 which is a difference of 13.6%. However it is thought by the author that it is encouraging that they are both of the same magnitude and the value of 2.86 is possibly an over-simplification of what is a complex process.

Looking at figures 4 and 5 and recapping what was said earlier in the paper, we need to change the process conditions and decrease the Zener-Holloman parameter thus increasing the recrystallisation temperature. From figure 4 it would seem that if we can obtain a Zener-Holloman parameter of less than 1.4 x 10^{10} s^{-1} (i.e. less than the value at the PCG interface) then the microstructure would be more resistant to recrystallisation and the formation of PCG during the solution heat treatment. Another issue to take into consideration is the effective strain. Although this is essentially a function of the extrusion ratio a larger strain would encourage recrystallisation at a lower temperature.

In order to test this hypothesis, with everything else remaining the same (including the distance from the front end), a die and the associated process conditions were tailored and modelled using finite element modelling to give a Zener-Holloman parameter of less than or equal to 1.4 x 1010 s-1 at the periphery of the bar. Unfortunately due to commercial sensitivity no process or design parameters can be revealed for Die X. Figure 6 shows the Zener-Holloman parameter for the particular die, which actually did turn out to be 1.4 x 10^{10} s^{-1} at the periphery of the bar. Also a bi-product of the design was that the strain was modelled to be relatively con-

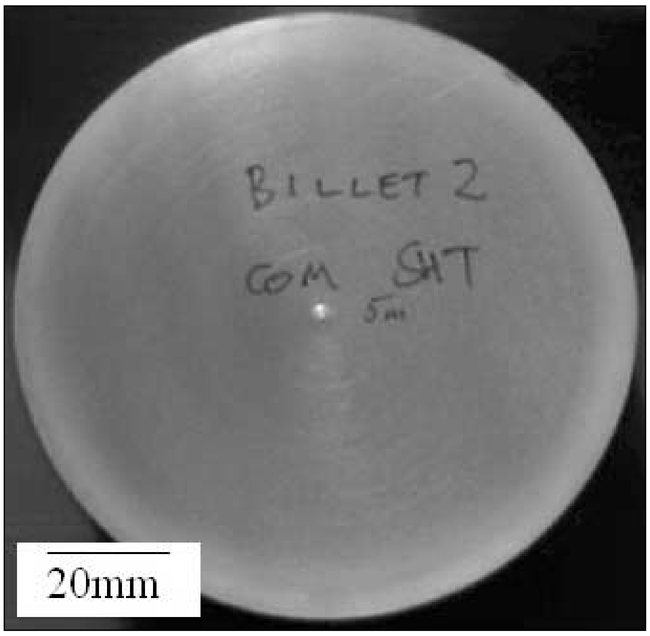

Figure 7: Macro-etched slice from Die X extruded bar

Figure 7: Sezione macro-attaccata di una barra X estrusa

stant throughout the thickness of the bar at 4.42 ± 0.1 although this strain is approximately 25% greater than for the flat die and so could have implications on the recrystallisation temperature.

As for the flat die a disc was cut 5m from the front end, ground and macro-etched. This is shown in figure 7 and as can be seen, no PCG is evident even after solution heat treatment. Although, there is 'shadowing' around the periphery of the bar, which indicates some change in microstructure, compared to the 'core'. The analysis of this material is ongoing and as such there are no optical micrographs but it is thought that the initial results look promising. It would seem that for this particular case the Zener-Holloman parameter is a good indication of the behaviour of the microstructure. Of course it has to be acknowledged that if the billet composition or the homogenisation treatment change then this would alter the flow stress behaviour of the material and it would have to be remodelled. However, what these results do illustrate is that with a combination of finite element modelling, laboratory work and some commercial trials a specific problem can potentially be solved.

CONCLUSIONS

The preliminary results of an investigation into the formation of PCG within 2014A have been presented. The aim of this study was to demonstrate the ability to combine finite element modelling, laboratory work and commercial scale trials in order to optimise an extrusion process. The results are presented as a technique, which could be applied to many other problems in extrusion. With the advent of faster computers and new software the modelling of the whole extrusion process is now a reality although the time scales for modelling are still too long for day to day usage they are ideal for targeting specific problems.

PCG was found to form to a depth a 3.15mm when the 2014A was extruded through the flat die. Point tracking indicated that for this particular case if a Zener-Holloman parameter of less than 1.4 x 10^{10} s^{-1} is achieved then this would restrict the formation of PCG during a subsequent solution heat treatment. After changing the die design and the process parameters the Zener-Holloman condition was satisfied and material extruded through this die showed no initial signs of PCG. Further work is needed to examine what contribution the strain gradient makes towards the recrystallisation process and further work is also needed on the friction and heat transfer coefficients inputted into the finite element modelling. However, the initial results fit well to what is expected both theoretically and in reality.

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A B S T R A C T

PREVISIONE DELLE MICROSTRUTTURE ESRUSE USANDO TECNICHE DI MODELLAZIONE SPERIMENTALE E NUMERICA

KEYWORDS: allluminio e leghe, estrusione, metallurgia fisica

L'alluminio è un materiale importante che trova un sempre crescente numero di impieghi. Tuttavia, con l'aumetare delle sue applicazioni crescono le esigenze in termini di proprietà meccaniche e fisiche. Dopo la colata di una lega specifica l'unico metodo per alterarne la microstruttura e quindi le proprietà consiste nel processo termomeccanico.
In alcuni casi gli estrusori richiedono una particolare microstruttura finale per ottenere proprietà meccaniche specifiche per motivi di sicurezza del prodotto, per esempio nelle applicazioni strutturali. In altri casi la microstruttura risultante, anche se indesiderabile, è una parte quasi accettata del processo, per esempio grani periferici grossi nell'estrusione delle leghe dure. In questo studio, è stata studiata la formazione della microstruttura finale di pezzi estrusi in funzione delle deformazioni, dei tassi di deformazione e delle temperature prodotte nel processo di estrusione dell'alluminio. Le stesse deformazioni, tassi di deformazione e le temperature sono funzione di una particolare progettazione e di un controllo processo dell'estrusione.
Le indagini sono state effettuate usando una combinazione di metallo estruso industrialmente, esperimenti di laboratorio e modellazione degli elementi finiti condotti per l'intero processo di estrusione.
Questa memoria presenta lo stato dell'arte dello sviluppo delle tecniche fondamentali che possono essere utilizzate nel settore per predire le microstrutture dei prodotti estrusi. Lo scopo finale è che le stesse tecniche possono essere usate per determinare i parametri di progettazione degli stampi di estrusione ed del controllo processo per produrre le microstrutture richieste.