

BEHAVIOUR OF PARTIALLY RECRYSTALLISED STRUCTURES OF Al-1Mg DURING MULTIPASS HOT ROLLING

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Abstract Over the past few years, experimental effort has been directed to quantifying the recrystallisation behaviour of commercial aluminium alloys during thermomechanical processing, as a demand from the development of physically based models. However, little attention has been paid to the behaviour of partially recrystallised structures upon annealing. This paper reports on multipass hot rolling tests carried out on uniform thickness and tapered slabs in order to investigate the recrystallisation behaviour of partially recrystallised structures of an Al-1Mg alloy. The recrystallisation kinetics of partially recrystallised structures, which have been rolled and subsequently annealed, follows closely an Avrami equation. A law of mixtures in characteristic recrystallisation time and in recrystallised grain size can be used to describe the behaviour of partially recrystallised structures upon annealing as a first approximation, but experimental observations indicate that microstructural transients cannot be neglected.

Keywords: *accumulation of strain, partial recrystallisation, multipass hot rolling, recrystallisation.*

Introduction

Modelling the microstructural evolution in aluminium alloys during multipass hot rolling has proved to be a difficult task, although important contributions have been put forward [1-4]. However, the behaviour of partially recrystallised structures has received little attention [5-10], and to date, only empirical approaches are available which do not fully capture the basic physical metallurgy. Furthermore, although transients in flow stress and microstructure have been observed during multipass hot deformation for continuous and instant changes in Zener-Hollomon parameter, current models neglect them. Finally, fundamental effects observed experimentally such as strain path and strain reversal are ignored.

Previous research [5] had determined the kinetics of recrystallisation of an Al-1Mg alloy after deformation 2, when no, partial or complete recrystallisation occurs after deformation 1 in plane strain compression (PSC) at 400°C. It was found from stress restoration data that when partial recrystallisation occurs after deformation 1, Al-1Mg recrystallises in two stages. It was not certain whether this behaviour arised from the strain distributions present in the deformation zone in plane strain compressed specimens or from a fundamental effect of straining and recrystallising partially recrystallised structures, but precipitation of fine particles and later coarsening could have well accounted for it. This led to the rather unlikely proposal of an independent behaviour of both fractions during recrystallisation of a partially recrystallised structure. However, this type of behaviour contrasts with that observed in C-Mn steel austenites [7,8] and in type 316 stainless steels [9], for which sigmoidal curves have been reported. The results in the present work also disagree with two stage recrystallisation curves for partially recrystallised structures, as will be shown later.

This paper deals the recrystallisation behaviour of partially recrystallised structures, which has been investigated by double deformation - hot rolling - tests on uniform thickness slabs and on originally tapered slabs.

Experimental procedure

The chemical composition of the Al-1Mg alloy employed in the present work, which was prepared as part of a major Brite-Euram project [3], as well as the geometry of the uniform thickness and tapered slabs has been shown elsewhere [11,12]. Table 1 shows a detailed description of all the rolling tests, which were carried out in a fully instrumented two-high 50 tonne Hille mill, with two electrically-heated muffle type furnaces situated to either side to perform annealing treatments, while a third electrically-heated furnace was employed for reheat operations.

Table 1. Experimental matrix for double deformation tests on tapered and uniform thickness slabs indicating the processing parameters.

Test	Reheat T (°C)	Roll T ₁ (°C)	ϵ_1	Anneal T ₁ (°C)	Anneal t ₁ (s)	Roll T ₂ (°C)	ϵ_2	Q	Anneal T ₂ (°C)	Anneal t ₂ (s)	G
I	510	505	≤ 0.71	450	35	450	0.3	No	400	Various, Q	T
II	395	385	0.71	350	$t < t_{0.05}$	371	0.5	Yes	400	Various, Q	U
III	395	385	0.71	350	433	371	0.5	Yes	400	Various, Q	U
IV	395	385	0.71	350	1800	371	0.5	Yes	400	Various, Q	U
V	455	445	0.71	400	$t < t_{0.05}$	400	0.5	Yes	400	Various, Q	U
VI	455	445	0.71	400	50	400	0.5	Yes	400	Various, Q	U
VII	455	445	0.71	400	79	400	0.5	Yes	400	Various, Q	U
VIII	455	445	0.71	400	180	400	0.5	Yes	400	Various, Q	U

Q: Cold water quench; G: Geometry (T: Tapered slab; U: Uniform thickness slab); * Rolled as in a reversible mill.

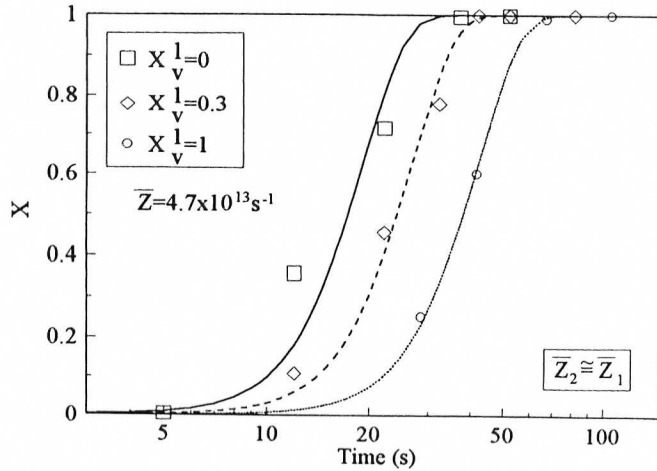
Two groups of tests were carried out using uniform thickness slabs. Tests II-IV in which the average Zener-Hollomon parameter was maintained approximately constant in both rolling passes ($\bar{Z}_2 \approx \bar{Z}_1$), by manipulating the initial rolling temperature, and tests V-VIII in which the average Zener-Hollomon parameter was allowed to increase from pass 1 to pass 2 ($\bar{Z}_2 > \bar{Z}_1$). These tests were complemented with tests on tapered slabs (I) in which $\bar{Z}_2 > \bar{Z}_1$ always held. All uniform thickness slabs were quenched after the second pass and later annealed in a salt bath at 400°C.

Whenever fraction recrystallised and recrystallised grain size measurements were involved, the samples were ground on successively finer silica papers and mechanically polished with diamond compounds. The final polishing was carried out with a colloidal suspension of SiO₂ in water. After polishing, the samples were anodised in Barker's etch at 20 V DC. An optical microscope equipped with a micrometer stage and a point counter device was used to perform the measurements while the sample was observed under crossed polarisers.

Results and Discussion

Fig. 1 shows the kinetics of recrystallisation after rolling pass 2 when no, partial or complete recrystallisation takes place after rolling pass 1, for $\bar{Z}_2 \approx \bar{Z}_1$. It can be seen that the data can be fitted closely by using an Avrami equation in the three cases, in agreement with the behaviour observed in C-Mn steels [7,8] and type 316 stainless steels [9].

Fig. 1. Static recrystallisation kinetics after rolling pass 2 when no, partial or complete recrystallisation occurs after rolling pass 1. Uniform thickness slabs ($\bar{Z}_2 \approx \bar{Z}_1$) (Tests II-IV).



Furthermore, Fig. 2 and 3 show the kinetics of recrystallisation after rolling pass 2 when no, partial or complete recrystallisation takes place after rolling pass 1, for $\bar{Z}_2 > \bar{Z}_1$; the partial recrystallised structures also follow closely an Avrami equation. Results from tapered slabs (Test I) also show sigmoidal curves to describe the recrystallisation kinetics of partially recrystallised structures, as shown in Fig. 4. The present results for partially recrystallised structures are thus inconsistent with two stage recrystallisation curves. It is important to mention that the 100% curve ($X_v^1 = 1$) in Fig. 1-3 has been corrected for differences in grain size. This correction is required because the 0% curve accumulates the strain according to an original grain size of 89 μm , whereas the 100% curve has a recrystallised grain size of 54 μm (when $\bar{Z}_2 \approx \bar{Z}_1$) or 61 μm (when $\bar{Z}_2 > \bar{Z}_1$), which becomes an original grain size for recrystallisation after rolling pass 2. The correction was done using an average dependence on d_0 , that is $t_{0.5} \propto \sqrt{d_0}$ and $d_{\text{rex}} \propto \sqrt{d_0}$, adequate to describe the behaviour of the present alloy within the processing conditions employed [13].

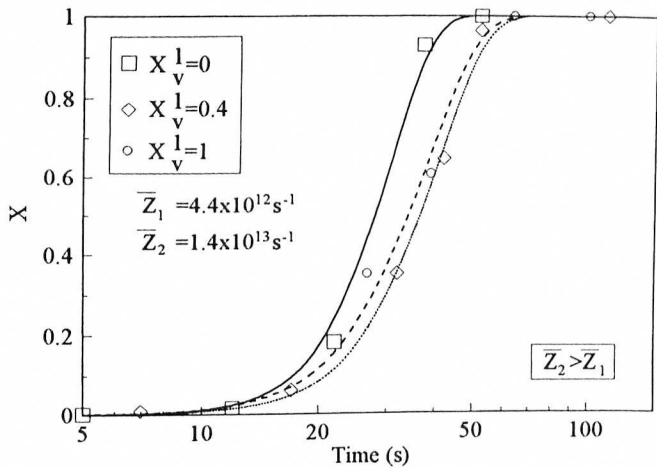


Fig. 2. Static recrystallisation kinetics after rolling pass 2 when no, partial or complete recrystallisation occurs after rolling pass 1. Uniform thickness slabs ($\bar{Z}_2 > \bar{Z}_1$); tests V, VI, VIII.

Fig. 1 also shows that the 30% curve lies between the 0 and 100% curve. In fact, a law of mixtures in $t_{0.5}$ can be used, in which case the expected $t_{0.5}^{30\%}$ can be calculated by using the relationship

$$t_{0.5}^P = X \cdot t_{0.5}^{100\%} + (1 - X) \cdot t_{0.5}^{0\%} \tag{1}$$

where $t_{0.5}^{100\%}$ is the time for 50% recrystallisation for the 100% prior recrystallisation curve and $t_{0.5}^{0\%}$ is the time for 50% recrystallisation for the 0% curve. Thus $t_{0.5}^{30\%} = 0.3 \cdot 37.7 + 0.7 \cdot 17.2 = 23.4$ s, which compares remarkably well with the measured 24 s.

Fig. 3. Static recrystallisation kinetics after rolling pass 2 when no, partial or complete recrystallisation occurs after rolling pass 1. Uniform thickness slabs ($\bar{Z}_2 > \bar{Z}_1$); tests V, VII, VIII.

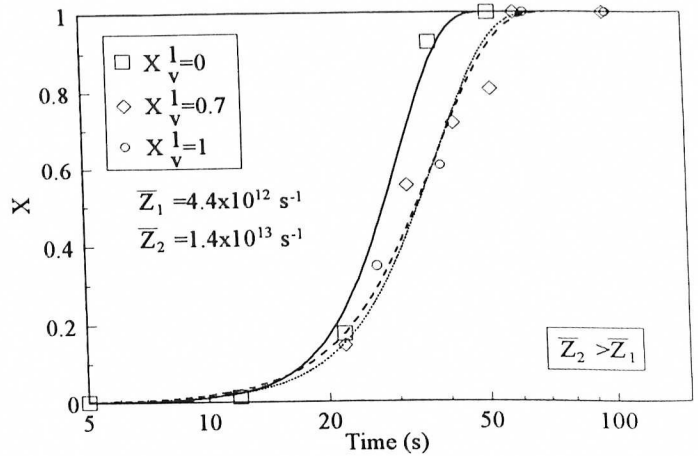
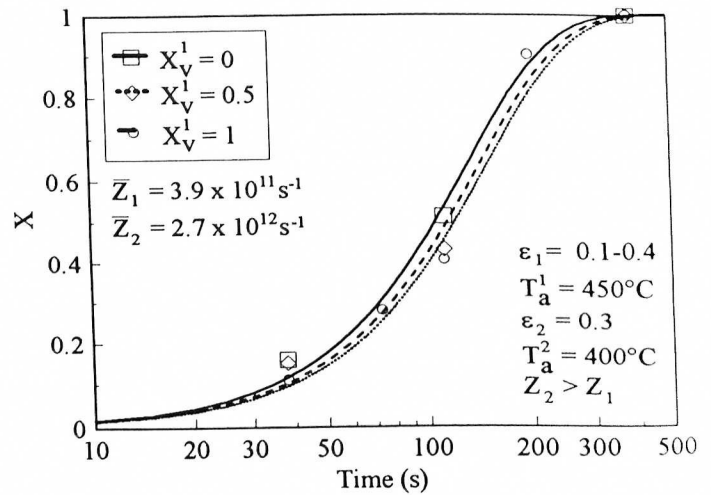


Fig. 4. Static recrystallisation kinetics after rolling pass 2 when no, partial or complete recrystallisation occurs after rolling pass 1. Tapered slabs ($\bar{Z}_2 \approx \bar{Z}_1$), test I.



Similarly, for recrystallised grain size, the expected $d_{rex}^{30\%}$ can be calculated, by using the equation

$$d_{rex}^P = X \cdot d_{rex}^{100\%} + (1 - X) \cdot d_{rex}^{0\%} \quad (2)$$

where $d_{rex}^{100\%}$ and $d_{rex}^{0\%}$ are the size of the grains in the regions which were recrystallised and unrecrystallised prior to a rolling pass, respectively. $d_{rex}^{100\%}$ and $d_{rex}^{0\%}$ are also the size corresponding to the 100% prior recrystallisation curve and the 0% curve, respectively. Thus $d_{rex}^{30\%} = 0.3 \cdot 57 + 0.7 \cdot 35 = 41.6$ μm , which is quite close to the measured 38 ± 2 μm . Therefore, the experimental evidence is in agreement with a law of mixtures in $t_{0.5}$ and d_{rex} for partially recrystallised structures. The close agreement is also a good indication that static recovery between

two deformations does not affect the kinetics of static recrystallisation after the second deformation at this temperature, in agreement with prior work [14,15].

However, for cases where $\bar{Z}_2 > \bar{Z}_1$ (Fig. 2 and 3), the 40% and 70% curves practically coincide with the 100% curve and none of the available empirical approaches is adequate to describe these results. Furthermore, results from test I (Fig. 4) also showed partial recrystallisation conditions being shifted to even longer times than the 100% curve. The difference in recrystallisation behaviour when $\bar{Z}_2 \approx \bar{Z}_1$ to that when $\bar{Z}_2 > \bar{Z}_1$, could be linked to the fact that microstructural transients occur in the latter case, leading to retarded recrystallisation kinetics, because some extra strain is required for the microstructure to reach steady state regimes, in agreement with recent work [16]. Hence the empirical approach - equation (1) and (2) - can only be applied as a first approximation to the problem.

Fig. 5 compares the effect of using a law of mixtures in $t_{0.5}$ with a law of mixtures in X

$$X^P = X \cdot X^{100\%} + (1 - X) \cdot X^{0\%} \tag{3}$$

where X^P is the recrystallisation curve (X, t) for the partially recrystallised structure, whereas $X^{0\%}$ and $X^{100\%}$ are the 0% and 100% recrystallisation curves, respectively. Notice that in the results in Fig. 5 $t_{0.5}^{100\%} / t_{0.5}^{0\%} \approx 2$, but the plateau in the partial recrystallisation curve still appears. Clearly, the behaviour of the partially recrystallised structure can be reasonably well described by either equation (1) or equation (3) in the present cases, although high values of the ratio $t_{0.5}^{100\%} / t_{0.5}^{0\%}$ are likely to worsen the results when equation (3) is employed.

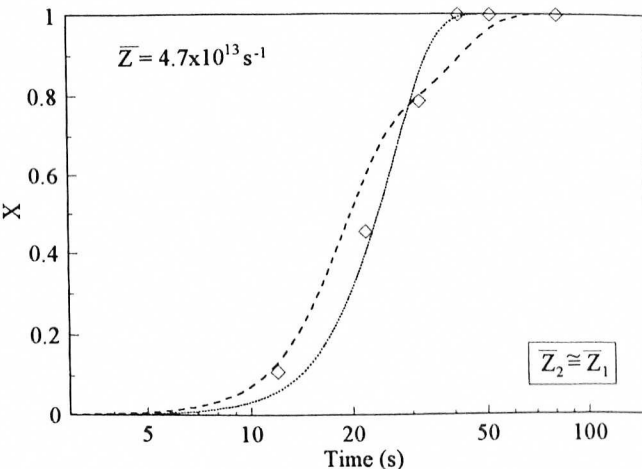


Fig. 5. Comparison of a law of mixtures in $t_{0.5}$ and in X to compute fraction recrystallised of partially recrystallised structures (Data points correspond to Test III).

Conclusions

The recrystallisation kinetics of partially recrystallised structures, which have been rolled and subsequently annealed, follows closely an Avrami equation. A law of mixtures in characteristic recrystallisation time and in recrystallised grain size can be used to describe the behaviour of partially recrystallised structures upon annealing as a first approximation. However, the approach may be too simplistic to cope with microstructural transients arising from the effect of varying hot deformation conditions, which are always present in hot rolling operations.

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