Recrystallization of an AIMgSi Alloy Deformed in Hot Torsion

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Abstract

The objective of the present investigation has been to provide knowledge about the development of microstructure and texture during recrystallization of material deformed in torsion. Recrystallization of an AIMgSi alloy has been studied, and the main focus has been on describing the development of nuclei in shear-deformed material. At medium and large strains, the Bs-component was seen to play an important role during recrystallization, and the origin of this component was consequently given special attention.

1. Introduction

The recrystallization process depends on the preceding deformation process, described by the deformation mode in addition to parameters such as strain, strain rate and temperature. During industrial deformation processes such as rolling and extrusion, the deformation is often seen to be a combination of different deformation modes. Lab deformation equipment exists that produce samples deformed in "pure deformation modes" such as plane strain compression and shear. Torsion testing is often used to produce material deformed in shear. In the present investigation the recrystallization texture and microstructure were studied in annealed torsion samples, in addition the as-deformed material was investigated in order to reveal possible nucleation mechanisms.

2. Experimental Methods

An AA6060-alloy (0.49 wt% Mg, 0.42 wt% Si, 0.20 wt% Fe and balance Al) was used for the experimental investigations. The as-cast starting material consisted of a coarse, equiaxed grain structure, and the average mean intercept length was measured to be 100 μ m. The texture in the starting material was close to random. Torsion specimens were machined from cylindrical cast and industrially homogenized billets of diameter 203 mm and length 7 m. The outer 2 cm of the billets were avoided to ensure a more homogeneous starting structure. The length and the radius of the gauge section of each torsion specimen were 10 mm and 5 mm respectively. Prior to deformation the material was re-homogenized at 580°C for 8 hours in an air-circulating furnace and then quenched in water. Deformation was carried out in torsion with various combinations of strain rates

and temperatures and to various strains (further details are found below). It is convenient in the present context to use the temperature compensated strain rate (Zener-Hollomon parameter); $Z = \dot{\varepsilon} \exp(U/RT)$, where $\dot{\varepsilon}$ is the strain rate, *U* is an activation energy, *R* is the gas constant and *T* the temperature. Throughout this work and activation energy of 156 kJ/mol has been used. For more details about the torsion experiments, see [1-3]. After the deformation the samples were annealed to obtain a partly or fully recrystallized microstructure. The annealing treatment was carried out by direct immersion of the testpieces into a salt bath with a temperature equal to the deformation temperature, keeping the samples at this temperature for various times and followed by water quenching.

Measurements of the global textures were carried out on a Siemens D5000 X-ray diffractometer. When making texture samples from the torsion specimens, the core of the specimens was removed, leaving a cylinder of 0.6 mm thick walls, which is cut longitudinally and subsequently flattened out. The outer surface of the flattened torsion specimen is then prepared by mechanical polishing, and etching in a solution of 15% NaOH and sugar for 15 minutes followed by 20 seconds in water and 20 seconds in a 25% HNO₃ solution. In the present work the texture is represented using Miller indices $\{hkl\}$ -uvw>. The $\{hkl\}$ -direction is parallel to the z-direction (the axis of the torsion sample) and <uvw> is parallel to the \$-direction (the direction of deformation), that is, the representation is on the form $\{z\}$ <\$>>. This makes the representation of the torsion textures comparable to the standard representation of texture from rolled and extruded material, when $\{hkl\}$ is parallel to the normal of the sheet and <uvw> is parallel to the extruse components were found in the as-deformed material:

- (A2) $\langle \overline{1} \overline{1} 1 \rangle \langle 112 \rangle$ and $\langle 11\overline{1} \rangle \langle 112 \rangle$
- (B1) $\langle \overline{1}12 \rangle \langle 110 \rangle$ and $\langle 1\overline{1}\overline{2} \rangle \langle \overline{1}\overline{1}0 \rangle$
- (C) $\{001\}(110)$

Optical microscopy and Scanning Electron Microscopy (SEM) equipped with an EBSD-unit were used to investigate the as-deformed, the partly recrystallized and the fully recrystallized material. The samples were examined in the $z\theta$ -plane, and care was taken to keep the distance from the center of the specimen to the plane of study the same in all the specimens. Standard specimen preparation was applied. The SEM was used both for mapping of orientations and for studying of the microstructure. Optical microscopy was mainly used for studying of the fully recrystallized material.

3. Results and Discussion

The material was deformed in torsion at Zener-Hollomon parameters ranging from $1.5 \cdot 10^8$ s⁻¹ to $2 \cdot 10^{12}$ s⁻¹, and with strains ranging from 1 to 35, Table 1. The temperature of deformation was kept above the solvus temperature to keep the hardening elements in solid solution during deformation. In the present paper, the torsion samples are considered the starting material, and for deformation data such as stress-strain curves, peak stress, microstructural evolution *etc.* will only be treated briefly. For a more thorough presentation of the torsion experiments, see Pettersen *et al.* [1-2]

During deformation at the lower angular velocity, there is a rapid rise in torque to an initial plateau. This part of the curve is consistent with similar experiments carried out in other deformation modes. In torsion, extra high strains are achievable compared to other deformation modes, and continuing straining the material reveals that this initial plateau only exists over a narrow region, followed by a gradual softening to a final steady state

regime. At the higher angular velocities the torque rises more gradually to the peak of the curve, corresponding to the gradual increase in the angular velocity. For details, confer [1].

The orientation image map in Figure 2 illustrates the development of the grain-boundary structure. During deformation the original grains changes their shape, and the surface area per unit volume increases with strain until a certain critical strain has been reached. At low strains and low Zener-Hollomon parameters the original grains could be distinguished as separate entities, separated by the original grain boundaries. The grains are elongated in a direction making a small angle with the shear direction, and the boundaries show a serrated appearance. Increasing the strain the original grains continue to elongate, and the grain boundaries from opposite sides of the grain will approach each other. Eventually, a structure of small equiaxed "grains", surrounded by high angle boundaries was observed. For further details on the deformed microstructure, confer [2].

Table 1: Experimental conditions for the torsion experiments. When calculating the actual temperature, the rise in temperature due to adiabatic heating and heat flow in the radial and axial directions have been accounted for.

Z [1/s]	Temperature [°C]	Strain rate [1/s]	Strain
1.5·10 ⁸	528	0.01	1, 2, 4, 10
2·10 ¹⁰	523	1.3	1, 2, 3, 5, 10, 25
7·10 ¹¹	486	13	1, 2, 3, 5, 25, 35
2·10 ¹²	476	21	1, 2, 4, 10

3.1 Development of deformation texture

The deformation texture was investigated using X-rays and orientation image mapping. The texture components A2, C and B1 were found, and the intensity at different Zener-Hollomon parameters and strains measured using X-rays are shown in Figure 1. As can be seen from the figure, at small strains the texture is very weak, containing only small amounts of the above listed components. The A2 and the C-components were found to be approximately equal in strength and slightly stronger than the B1-component. However, they were all present in negligible amounts. Increasing the strain from a value of 1 to a value of 2 or 3, the A2-component was found to decrease while the intensities of the B1-and C-components were increasing. The B1-component increased only slightly and was still weak compared to the C-component at a strain of 3.

From a strain of 3 to a strain of 5, the intensity of the exact C-component is seen to continue increasing to a value of 9-10, while the intensity of the exact B1-orientation increases to a value of 3 times random. That is, the intensity of the exact C-component is still considerably stronger than the B1-component at this strain. Increasing the strain above 5, the intensity of the C-component is seen to decrease, while the intensity of the B1-component is seen to become gradually stronger. At a strain of 10 ($Z=7\cdot10^{11}$ /s), the intensity of the B1-component is seen to be slightly stronger than the C-component. At a strain of 25, the C-component has vanished at the same time as the B1-component is seen to increase with strain at strains ranging from 1 to 25. However, increasing the strain further did not seem to involve a continuing increase in the intensity of the B1-component. In fact, a decrease in intensity of about 12% was found when increasing the strain from 25 to a value of 35.

3.2 Bs-oriented regions in the deformed material

One of the common texture components resulting from plane strain deformation of fcc metals is brass, Bs ($\{0\bar{1}1\}/(\bar{2}11)$) and $\{01\bar{1}\}/(2\bar{1}\bar{1}\bar{1})$). As will be shown below, this texture component also appears as a dominating recrystallization texture component after deformation in torsion, and it will be referred to as Bs also in this context. Hence, a search for the Bs-oriented regions in the deformed material was carried out in order to monitor potential nucleation sites. The appearance of Bs-oriented regions was found to be strongly dependent on strain. At small strains two different types of Bs-oriented regions were found. The orientation image microscopy (OIM) map shown in Figure 2a shows an elongated band of Bs-orientation, in addition, small groups of subgrains of the Bs-oriented bands were found. The lengths and widths of the bands were found to be close to what was expected from geometry. The areas adjacent to the Bs-oriented bands were characterized by orientation measurements and the results are displayed in Figure 3a. It can be seen that a large fraction of the Bs-oriented bands are surrounded by regions of random orientation, which indicates that there are no preferred neighboring orientations.







At large strains the Bs-orientation was solely present as single subgrains or small groups of subgrains (Figures 2b and 2c). The areas surrounding the subgrains were often found to be of the B1-orientation, and a gradual orientation change from the B1-orientation to the Bs-orientation by rotation around a mutual <111>-axis was commonly observed. To obtain a quantitative measure of this phenomenon, the orientation of subgrains close to the Bs-oriented regions were monitored, and the results are as displayed in Figure 3b. As can be seen from the figure, the great majority of the neighboring subgrains were of an orientation. Just a small fraction of the surrounding subgrains were of the C- or the random orientation. This indicates that the Bs-regions have been formed by rotation of the boundary region of the B1-oriented bands. The fraction of C-oriented bands decreases with strain. The

regions of random orientation were seen to be similar to the regions of the Bs-orientation, that is, the random oriented subgrains either formed small groups or single subgrains. The fraction of subgrains of random orientation was however found to decrease dramatically with strain from a strain of 5 to a strain of 25, compared to the fraction of subgrains of the Bs-orientation which was found to be approximately constant in the same strain range.

3.3 The partly recrystallized material

In order to be able to investigate the course of the restoration process in the deformed material, the material was annealed to various stages of softening and then quenched. Using OIM, the orientations of the new grains were recorded, and the results for one Zener-Hollomon parameter are shown in Table 2. It can be seen that the number of new grains of the Bs-orientation increases with strain. This is in accordance with increasing intensity of Bs with strain in the fully recrystallized material. The Bs-oriented growing grains were found to be on average larger than the growing grains of other orientations. This was particularly the case at the highest strains, and at a strain of 25 the size difference was estimated to be about 1:5. The density of potential grains was found to increase with strain.





Figure 2: OIMs showing subgrains of the Bsorientation as shaded areas. The maps are from material deformed at Z= $7 \cdot 10^{11}$ /s, and to strains of a) ε =1, b) ε =5 and c) ε =25. A boundary is designated a high angle boundary (heavy line) if the rotation angle is greater than 15°, and as a low angle boundary (thin line) if the orientation difference lies below 15° and above 1.5°.

3.4 Evolution of recrystallization microstructure and texture

The main objective of the macro-texture measurements of the fully transformed material was to investigate the effect of strain on the texture development during annealing. At the lowest Zener-Hollomon parameters the grain size is relatively large, and the statistics for the texture measurements becomes poorer, the present description is hence restricted to Zener-Hollomon parameters including and above $Z=7\cdot10^{11} \text{ s}^{-1}$. Polefigures were obtained for prior strains ranging from 1 to 35, and the texture was seen to change from close to random to a strong Bs-texture. At the lowest strains a very weak, nearly random annealing texture was observed. Increasing the strain to $\varepsilon=3$ the texture is still weak, but small amounts of the Bs-component is now observed. The Bs-component is $30^{\circ} <111>$ oriented with respect to the B¹-component found in the as-deformed material. At a prior strain of $\varepsilon=5$ the Bs-component is clearly visible, and has a maximum intensity of about 6 times random. The intensity of the Bs-component continues increasing, and at a prior strain of 25 it has reached an intensity of approximately 22 times random. Further increasing the strain does not seem to have the same effect on the annealing texture. At a strain of 35

the intensity of the Bs component has decreased to about 15. Hence, there seems to be a close relationship between the observation of the B1-component in the deformation texture and the Bs-component in the annealing texture.



Figure 3: Results from OIM. a) Fraction of grains of various orientations surrounding the Bs-oriented bands. The measurement was carried out in the material deformed at $Z=7\cdot10^{11}$ /s deformed to a strain of 1. The values have been obtained by scanning about 1700 µm of the boundary area of the Bs-oriented bands. b) Orientations of the regions surrounding the Bs-oriented subgrains. The notation $\theta <111>$ corresponds to the B¹-orientation rotated at an angle θ around the <111>-axes. θ is approximately 15°. The figure is based on measurements in the vicinity of 20 subgrains of the Bs-orientation for each deformation condition.

Table 2: The number of potential new grains of the Bs-orientation and other orientations for a selection of deformation conditions. The data have been collected from OIM in partly recrystallized material. The specimens were annealed for 5 seconds at 480°C.

Z [s ⁻¹]	Strain	Bs	Other
7·10 ¹¹	1	10 (15%)	57 (85%)
	3	47 (23%)	157 (77%)
	5	113 (41%)	166 (59%)

4. Conclusions

In the present investigation the recrystallization texture was studied in annealed torsion samples. At large prior strains the texture is seen to be dominated by the Bs-component. In the deformed material at small strains, regions of the Bs-orientation are present as elongated bands and small regions containing one subgrain or a small group of subgrains.

When increasing the strain a deformation texture consisting of mainly the B1- and the Ccomponents was seen to develop, however, small island regions of Bs-oriented grains were also found. The Bs-grains were exclusively seen to be surrounded by high angle boundaries, and provided they have a size advantage, they make ideal sites of nucleation. The Bs-orientation seems to form during deformation in torsion by a 30°<111> rotation of small regions in the boundary region of the B-oriented bands.

References

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