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Development of Recrystallized Structure During Hot Deformation of Al-Mg-Li-Zr-Sc Alloy

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Abstract

In conditions of laboratory modeling the influence of temperature (250-500°C) strain rate (10^{-3}–10^{-1} and $8 \cdot 10^{2}$ s^{-1}) and deformation level (up to 90%) on the development of grain structure under hot deformation and heat treatment of 1424 alloy is investigated. It is established that a complete nuclear recrystallization is not reached both as the result of static and spontaneous recrystallization within the temperature and strain rate intervals investigated. For all of the deformation conditions investigated continuous recrystallization with the formation of fine equiaxed grains (of 2-4 μm) was observed. For compression deformations greater than 80% continuous dynamic recrystallization produces a fine grain equiaxed structure.

1. Introduction

Semiproducts of aluminium alloys, alloyed with Li, Zr, Sc in particular 1424 alloy, have higher resistance to recrystallization under heat treatment as compared with traditional alloys. The deformed fibrous structure and texture are retained under solid solution heat treatment (SSHT) and quenching and result in a strong anisotropy of mechanical properties. Removal of the fibrous structure can be achieved only as the result of recrystallization (discontinuous or continuous) or deformation grain fragmentation. For the discontinuous mechanism by nucleation (static) recrystallization is usually developed under heating of deformed metal and (spontaneous) recrystallization occurs directly after hot deformation.

Continuous recrystallization is less well understood and is seldom used for structure control. It consists of subgrain rotation with increasing of disorientation angles [1]. Grains formed by this process can contain low angle boundaries, that is they may exhibit a subgrain structure and, hence, be quite different from normal recrystallized grains [2]. Continuous recrystallization is observed more often during deformation (dynamic recrystallization).

It is known, that a fibrous structure may be transformed to an equiaxed one with grain size comparable to the subgrain size when deformed sufficiently to reduce grain thickness to the subgrain size [3]. Such a deformation results in an ultrafine grain, nearly equiaxed structure for practically all alloys.

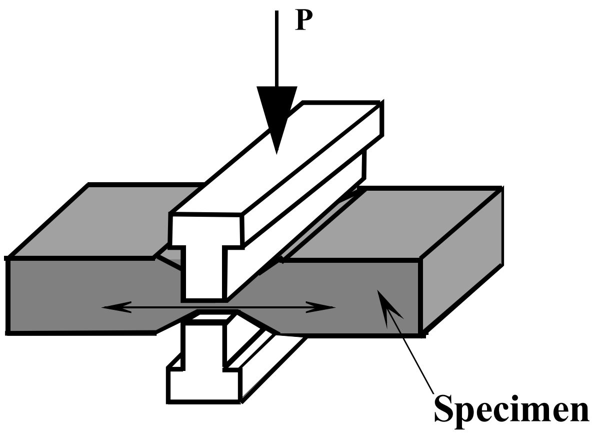
This process is realized more readily at high temperatures and low strain rates (small values of Z parameter) since a stationary subgrain size is defined by this parameter (d^{-1} ~ Z, Z = $\dot{\varepsilon} \cdot \exp Q/RT$ – Zener-Hollomon parameter, $\dot{\varepsilon}$ -strain rate, Q- hot-working activation energy, R- the gas constant, T- strain temperature, K) [4]. After the development of subgrain sized grains, further deformation does not change size and form of the grains.

In this work an influence of temperature and strain rate on deformed structure stability is studied and the possibility of oriented fibrous structure removal under hot deformation of 1424 alloy sheets is demonstrated

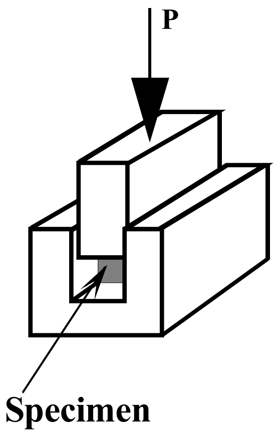
2. Material and Methods

Temperature and strain rate influence is studied on specimens cut from hot rolled 1424 alloy 9,4 mm thickness sheet containing: 1,7 %Li; 5,9 %Mg; 0,6 %Zn; 0,07 %Zr; 0,08 %Sc; 0,17 %Mn.

The deformation was carried out by two methods: plane strain compression of a plate form specimen between two rectangular section indenters (Figure 1a) and compression of specimen in channel die (Figure 1b). Deformation by plane strain compression is carried out on 9,4 mm thickness, 65 mm width and 30-35 mm length specimens between 7 mm wide indenters in special die. For deformation in the channel die specimens 9,4 mm thick, 10 mm wide, 10-20mm in length were used. Deformation was carried out on EU 100 hydraulic test machine with maximum effort of 100T and on vertical drop hammer of 5 m height with 30 kg falling weight.



a.



b.

Figure 1: Plane compression of specimens: a – plane strain compression; b – compression in channel die.

The deformation was carried out under isothermal conditions in the temperature rangel of 250-500°C and at constant ram speed. The initial strain rates were $2 \cdot 10^{-3}$, $6 \cdot 10^{-3}$ and 10^{-1} s^{-1}. Specimens were cooled in water in 30-60 s after the end of deformation. For the drop hammer tests the die with a specimen was heated up to the deformation temperature then deformation was carried out during 20-30 s and the specimen was cooled in water in 30-40 s after deformation ending.

The initial strain rate was $8{\cdot}10^{-2}\ s^{-1}$. At compression on the drop hammer the plane strain compression is not used, that is specimens are broken at strain degree less, than 50% because of low plasticity.

Study of the structure is carried out in the central, most deformed zone of specimen. It is necessary to note, that a deformation is very inhomogeneous along the specimen section. At average strain levels below 50% the maximum degree of deformation of the specimen, as determined from an analysis of a coordinate net was 80% in central layer. In this paper the strain degree average values on the thickness of specimens are discussed. Specimen structure was studied by methods of optical microscopy (OM, Neophot 21), TEM (BS 540), X-ray structural analysis (transmission photography under Mo-radiation).

3. Results and Discussion

The initial hot rolled 9,4 mm thickness sheet had a fine fibrous structure with an average fibre thickness of 2 µm. After solid solution heat treatment at 470°C and quenching the structure remained essentially unchanged in the central layers; a fine fibrous structure which was almost completely unrecrystallized, but with very few fine equiaxed grains (Figure 2). The fibres had an internal substructure, consisting of subgrains of 1-1,5 µm dimension in L direction and 0,5-1,0 µm dimension in ST direction with sufficiently small disorientation angles between them as to not be revealed by optical metallography. The small thickness of initial fibres suggested, that even at comparatively small deformation degree it could be compressed to subgrain size, and the fibrous structure reformed into an equiaxed one. For the highest temperature and low strain rate (small Z) this condition ($D{\sim}d_s$) has to be fulfilled at initial deformation stage.

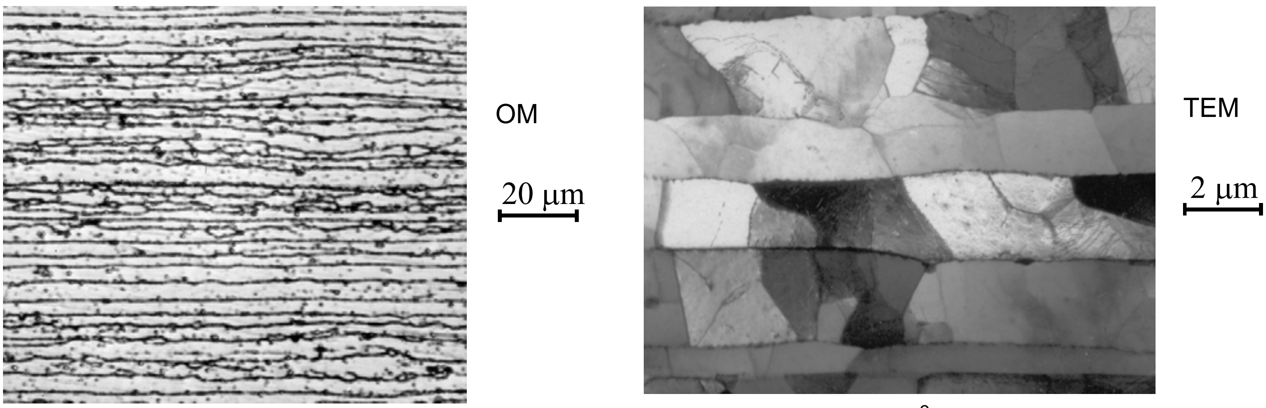
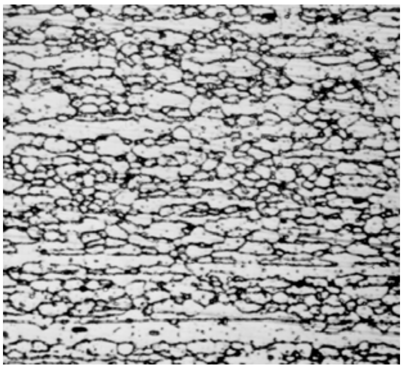
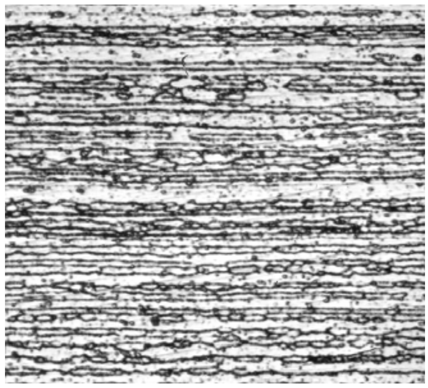


Figure 2: Microstructure of hot rolled and heat treated (470°C, 1 h + 170°C, 3 h) 1424 alloy sheet.

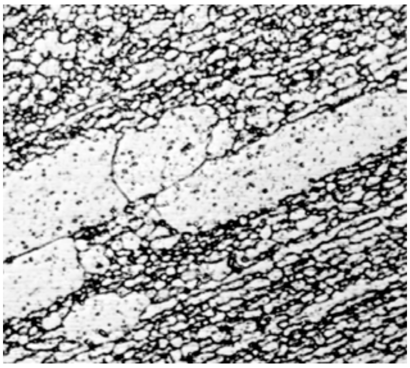
Specimens deformed at 450°C to 50% degree strain and heat treated structures are shown in Figure 3.



$\dot{\varepsilon} = 10^{-1}\ s^{-1}$



$\dot{\varepsilon} = 8{\cdot}10^{2}\ s^{-1}$



$\dot{\varepsilon} = 8{\cdot}10^{2}\ s^{-1}$
(microstructure
in shear band)

OM 20 μm

Figure 3: Microstructure of specimen com pressed and heat treated (470°C, 1 h +170°C, 3 h) alloy.

A mixed structure consisting of fine equiaxed grains, formed as result of continuous recrystallization, and areas with fibrous structure were observed on specimens deformed at low strain rate (10^{-3}–10^{-1} s^{-1}). The volume fraction of equiaxed grains increased with increase in temperature and (or) decrease in strain rate. By TEM it was revealed that the specimen structure consisted of fine (1–3 μm) grains and subgrains. At the highest deformation rates (>10^{2} c^{-1}) the deformation structure was significantly different (Figure 3). First, the deformation was very inhomogeneous with a formation of shear bands, analogous to those formed during cold working. Secondly, discontinuous recrystallization is realized along shear bands during cooling. The comparison of structure before and after heat treatment of specimens allowed us to establish that, at the high temperatures (> 375°C), recrystallization starts during cooling of the specimens after deformation (spontaneous) and, at the lower temperatures, recrystallization is realized only under heat treatment (static recrystallization). At the maximum temperatures (> 450°C) it is requested additional confirmation of static recrystallization development or coarse grains is formed as result of spontaneous recrystallization, which can get after study of recrystallization kinetic. Outside shear bands the structure is unrecrystallized fine fibrous with small part of fine equiaxed grains.

On the basis of a study of the results of structure in specimens deformed to 50% and then heat treated at the temperature of 470°C a structure state diagram (SSD) has been plotted [6] in coordinates of “strain temperature – strain rate” (Figure 4). The lines of lg Z equal values calculated for Q = 157 kJ/mol are plotted on the diagram as an additional coordinates net. The diagram consists of several areas (regions). Region I includes deformation regimes at which nuclear recrystallization is absent.

Region II of complete recrystallization is absent on SSD. In region III partial static nuclear recrystallization is observed and in region IV – partial spontaneous nuclear one. For used initial structure a continuous recrystallization is realized in all regions. Part of limit lines on SSD is plotted dotted ones, since its exact position is not established.

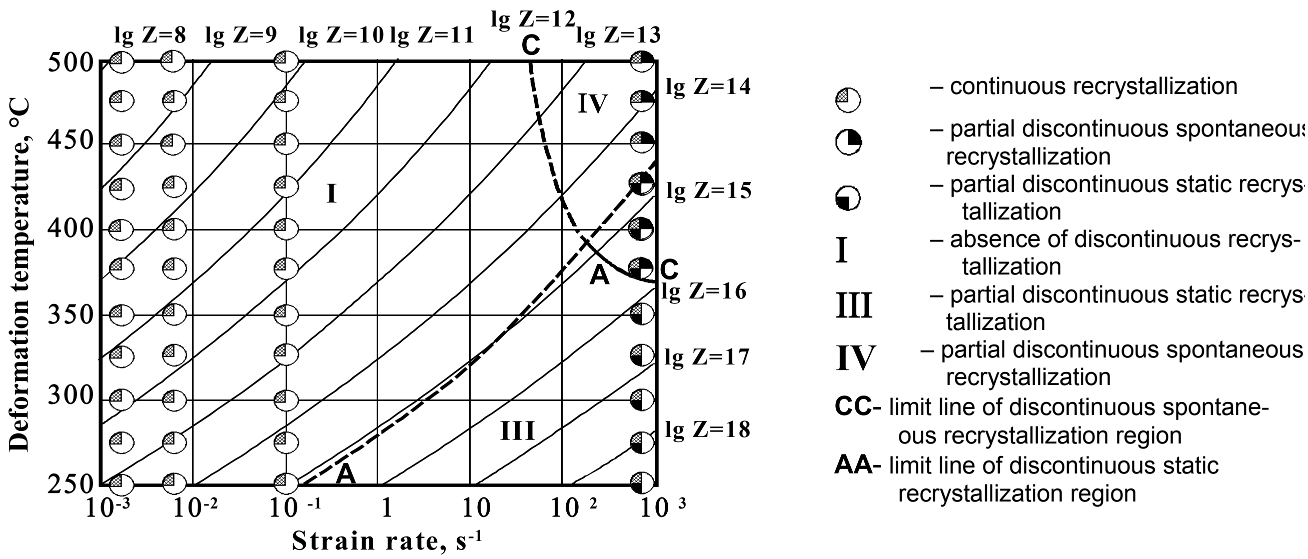


Figure 4: SSD for hot-worked to 50% and heat treated specimen (470°C, 1h).

As to the influence of deformation degree on the structure, the fraction of equiaxed structure in deformed and heat treated specimens increases with strain degree for all regimes and under high degree can achieve 100%. Fine grains of 2–4 μm dimension have sufficient disorientation to allow detection under polarized light (Figure 5).

After big strain degree on X-ray images of specimens with fine equiaxed structure produced by high deformation levels reveal erosion of the texture maximum, testifying to the increase of disorientation angles in the structure elements and weakening of the crystallographic texture. The deformation level at which complete transformation of fibrous structure to an equiaxed one is achieved decreases as temperature increases and (or) strain rate decreases (Z parameter decrease). Average values of deformation level after which the completely equiaxed structure is observed are:

74%for $\theta = 500°C$ and $\dot{\varepsilon} = 2 \cdot 10^{-3}\ s^{-1}$;
83% for $\theta = 400°C$ and $\dot{\varepsilon} = 2 \cdot 10^{-3}\ s^{-1}$; and
84% for $\theta = 350°C$ and $\dot{\varepsilon} = 6 \cdot 10^{-3}\ s^{-1}$.

The local deformation is essential higher for central layer of specimen in which a complete equiaxed structure is observed. The stated levels above are close to the minimum necessary ones to develop the equiaxed structure at the various temperatures and strain rate, but exact values have not been defined in this work.

Grains have close to equiaxed form with relation of length to thickness ~ 1,3-1,5. Those average values are 2-4 μm (table 1) and decreases under decrease of temperature and (or) increase of strain rate. By TEM it was found that basic elements of the structure have 2 × 1,6 μm average sizes for specimens deformed at 350°C with strain rate of $6 \cdot 10^{-3}\ s^{-1}$ and strain degree of 87%.

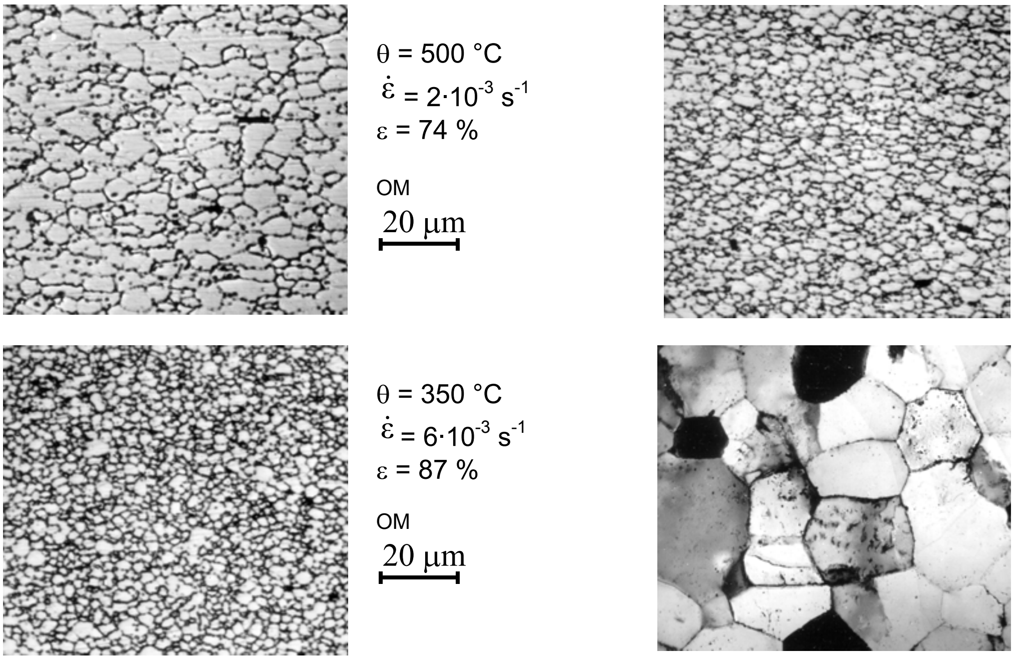


Figure 5: Microstructure of specimens compressed to high strain levels and heat treated (470 °C,1 h + 170 °C, 3 h).

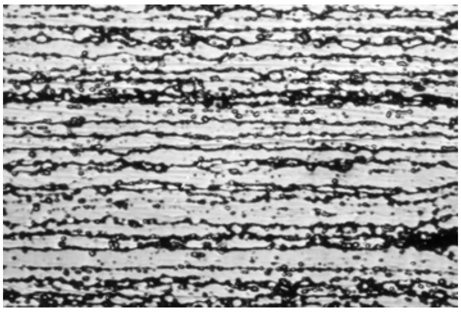
After solid solution heat treatment at 515°C static recrystallization starts in the some specimens deformed at low temperatures and having equiaxed structure, that indicates comparatively not high thermal stability of continuous recrystallized structure.

Table 1: An average grain size for compressed specimens.

Strain parameters			Followed SSHT	D, μm tensile direction	D, μm compression direction
θ, °C	$\dot{\varepsilon}$, s^{-1}	ε, %			
350	$6 \cdot 10^{-3}$	87	470	1,7	1,4
400	$2 \cdot 10^{-3}$	83	470	2,3	1,5
400	$2 \cdot 10^{-3}$	83	515	2,7	2,1
500	$2 \cdot 10^{-3}$	74	–	3,7	2,4
500	$2 \cdot 10^{-3}$	74	470	3,8	2,6
500	$2 \cdot 10^{-3}$	74	515	4,3	2,8

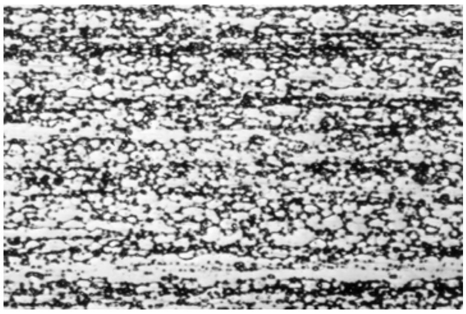
The forming of fine equiaxed structure by continuous recrystallization mechanism is the most perspective at a manufacture of wrought semiproducts by the extrusion, at which low strain rates are realized. Angle extrusions with 3 and 4 mm thickness flanges manufactured against two regimes distinguished with total reduction have different structure (Figure 6).

The angle extrusion manufactured with reduction ≈24 has (1) fibrous structure and separate fine equiaxed grains (Figure 6a). For the angle extrusion manufactured by two stage with total reduction ≈32 (2), essential part of structure consists of fine equiaxed grains (Figure 6b). This part increases of central to surface along angle section, that is caused unhomogeneously of deformation.



a

OM 20 µm



b

OM 20 µm

Figure 6: Microstructure of 1424 alloy, extruded against 1 (a) и 2 (b) regimes.

4. Conclusion

1. In conditions of laboratory modeling the influence of temperature (250-500°C) strain rate (10^{-3}–10^{-1} and $8 \cdot 10^{2}$ s^{-1}) and degree (up to 90%) on the forming of a grain structure under hot deformation and heat treatment of 1424 alloy is investigated. The study of deformed and heat treated specimen structure results in definition of limit lines on the structure state diagram of 1424 alloy. It is established, that a complete nuclear recrystallization is not reached both as the result of static and spontaneous recrystallization in the investigated temperature and strain rate interval. Within all these intervals continuous recrystallization with formation fine equiaxed grains (of 2-4 µm) is observed.
2. It is established, that for deformation by compression to levels higher than 80% it is possible to form an equiaxed fine grain structure with grain size of 2-4 µm as the result of continuous dynamic recrystallization. The strain degree, at which the fibrous structure is removed and an equiaxed structure is formed, increases and grain size reduces with decrease of temperature and (or) increase of strain rate. The thermal stability of fine equiaxed structure is defined by temperature rate condition of deformation (decrease under decrease of temperature and (or) increase strain rate) and can be not sufficient for its preservation at heat treatment.

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