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TWINNING AND SOFTENING OF CAST MAGNESIUM ALLOY AZ91 UNDER HOT COMPRESSION

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Cast magnesium alloy AZ91 is studied after uniaxial compression in the range from room temperature to 400°C. The alloy is tested for compression and its microstructure is determined. The values of the parameter of strain hardening are found. The main mechanisms of structural transformations developing under compressive deformation of alloy AZ91 at low and moderate temperatures are considered.

Key words: magnesium alloy, deformation, twinning, softening.

INTRODUCTION

The temperature range of deformation of magnesium alloys can be broken into three parts in accordance with the active deformation mechanism, namely, (*1*) a low-temperature region (below 200°C; controlled primarily by basal slip and twinning), (*2*) moderate temperatures (200 – 300°C; controlled by basal and non-basal slip) and (*3*) a high-temperature region (above 300°C; controlled by basal and non-basal slip, cross slip, and climb of dislocations) [1]. The deformation behavior of magnesium alloys at low and moderate temperatures permits elevation of the operating properties, saving of energy, and simplification of the deformation process. For example, a sheet from magnesium alloy with a thickness below 1 mm cannot be obtained by hot or warm rolling but only by cold rolling [2 – 4]. However, the majority of recent studies of magnesium alloys are devoted to their deformation behavior at high temperatures. Therefore, it is expedient to investigate the deformation behavior of magnesium alloys at low and moderate temperatures in order to develop a process for manufacturing sheet magnesium alloys at low temperatures.

The main mechanism of low-temperature deformation of magnesium alloys includes basal slip and twinning, which may cause both softening and hardening. Elevation of the deformation temperature is accompanied by twinning that affects different mechanisms of softening, i.e., dynamic retrogression and dynamic recrystallization [5]. Work [6] is devoted to the cast structure of cast magnesium alloy AZ31 after torsion at moderate temperatures (180 – 240°C). It is shown that the formation of twins in dynamic retrogression often finishes at some point near grain boundary. However, dynamic retrogression may give rise to serration on grain boundaries and twins. The relation between twinning and dynamic recrystallization at 50 – 200°C is studied in [7]. It is shown that the twinning-induced dynamic recrystallization occurs due to the accumulation of distortion energy in twins. The authors of [8] have studied a deformed magnesium alloy with special orientation of boundaries and observed softening and hardening effects induced by formation of contact twins and multiple twinning. However, these works do not consider the effects of softening and hardening that occur in twinning of cast magnesium alloys with random orientation of grains. Moreover, the relation between twinning and the mechanisms of dynamic recrystallization has not been confirmed with certainty.

The aim of the present work was to study the deformation behavior of cast magnesium alloy AZ91 at a temperature from room one to 300°C and to analyze the effects of its softening and hardening.

METHODS OF STUDY

We studied magnesium alloy AZ91 with the following chemical composition (in wt.%): 8.29 Al, 0.73 Zn, 0.2 Mn, 0.015 Fe, 0.04 Cu, 0.016 Ca, the remainder Mg. Cylindrical specimens 6 mm in diameter and 9 mm long were cut from an ingot with the help of an electric discharge machine for compressive tests. The compressive tests were performed using a Gleeble-1500 device at a constant deformation rate of 10^{-2} sec^{-1} in the range from room temperature to 300°C. Before testing, the specimens were held in an infrared fur-

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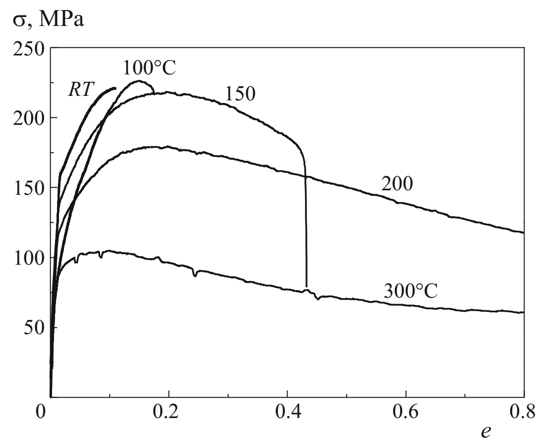


Fig. 1. Stress-strain curves for alloy AZ91 after compressive tests at a rate of 10^{-2} sec^{-1} at different temperatures (*RT* is the room temperature; σ is the true stress; *e* is the true strain).

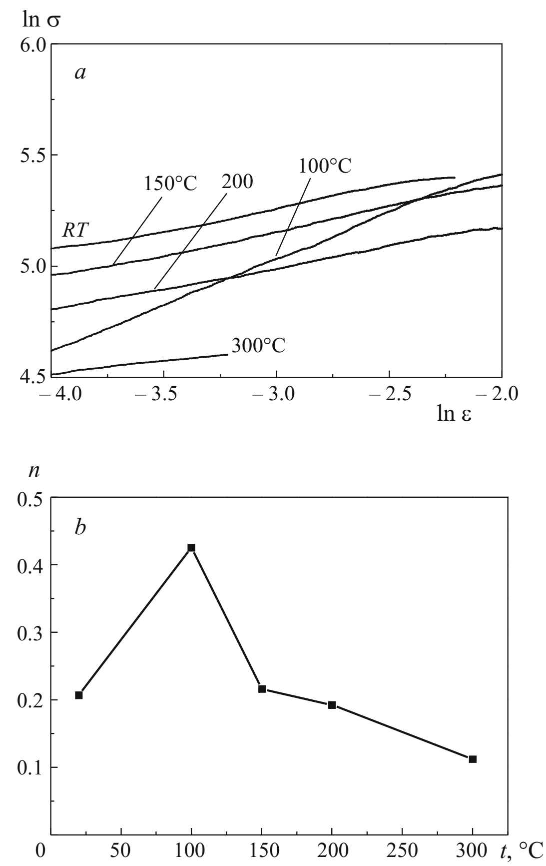


Fig. 2. Deformation curves for alloy AZ91 in logarithmic coordinates (*a*) and dependence of the parameter of strain hardening *n* on the temperature at a deformation rate of 10^{-2} sec^{-1} (*b*).

nace for 5 min for leveling the temperature over cross section. The specimen was lubricated by a Teflon tape. This was sufficient for avoiding bulging discernible by eye. After the tests the surface of the specimen was ground and polished by a conventional metallographic method. The laps were etched for 10 sec in a solution containing 19 ml water, 20 ml acetic acid, 1 ml nitric acid and 60 ml ethylene. The deformed pieces and the fracture surfaces were studied under a QUANTA 200 scanning electron microscope equipped with an energy dispersive spectrometer.

RESULTS AND DISCUSSION

Mechanical Properties

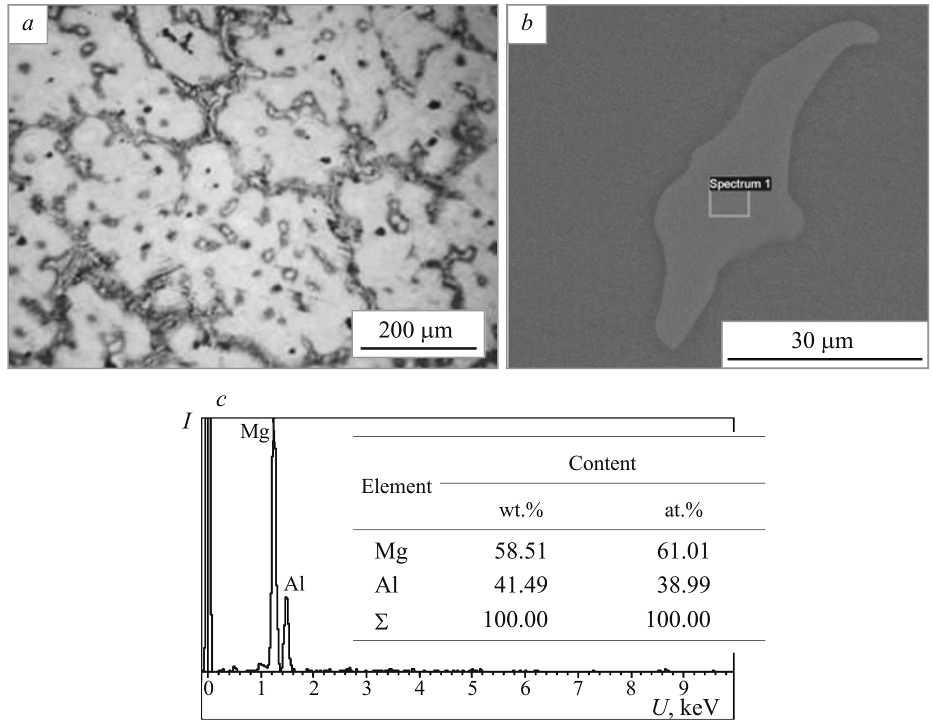
Figure 1 presents the flow curves of alloy AZ91 obtained in compression tests at different temperatures. It can be seen growth in the strain *e* at any studied temperature is accompanied first by a marked growth in stress σ and then by its decrease, most probably due to twinning. When the test temperature is increased, the peak stress of alloy AZ91 lowers and the softening range widens. It seems that the screw dislocations can move from flat pile-ups at grain boundaries to the neighbor slip planes by the mechanism of double cross slip, which is followed by annihilation of dislocations. It should also be noted that at a moderate temperature dynamic retrogression and dynamic recrystallization can play an important role in the softening. Tests at a temperature above 200°C have shown (Fig. 1) that the stress peaks on the stress-strain curves are followed by a steady softening stage connected with the development of dynamic recrystallization.

It is well known that after the start of flow of a metal the strain-hindering effects are intensified and the stress grows accordingly. To characterize such strain hardening, a strain hardening index *n* [8] and a strength coefficient *k* are used in the equation [9]

$$\sigma = k\,\varepsilon^n. \qquad (1)$$

In the present work the strain hardening index n was determined from the slope of the curve $\sigma = f(\varepsilon)$ in logarithmic coordinates. The curve was rectified for the range of strains lower than the strain of the attainment of the stress peak (Fig. 2*a*). To elevate the accuracy we determined the slope as a mean value for five points. The obtained values of n are presented in Fig. 2*b*. It can be seen that the index changes when the temperature increases over the curve with maximum at 100°C.

Due to the high value of the adjusted critical shear stress for slip $\langle c + a \rangle$, its activation at low temperatures is limited. For this reason twinning plays an important role at low and moderate temperatures and seems to influence strongly the softening and hardening effects [10]. In the general case the rates of strain hardening differ for different deformation mechanisms. Mechanical twinning can affect the deformation of magnesium alloys in two opposite directions, i.e., (*1*) like grain boundaries, twin boundaries serve barriers for the motion of dislocations, which increases the rate of strain hardening; in addition, twin boundaries transfer sliding dislocations into sessile dislocations inside the twins as a result of the hardening by the Basinski mechanism and (*2*) the act of twinning compensates the strain over the hexagonal axis,



Element	Content	
	wt.%	at.%
Mg	58.51	61.01
Al	41.49	38.99
Σ	100.00	100.00

Fig. 3. Microstructure (*a*, *b*) and results of an energy dispersive analysis of the region of cast magnesium alloy AZ91 put in frame in (*b*) prior to compression (*I* is the radiation intensity) (*c*).

which results in lowering of the rate of strain hardening. This means that twining in magnesium alloys may affect substantially both their softening and their hardening [8]. It is shown in [8] that the content of primary $\{10\bar{1}1\}$ twins and double $\{10\bar{1}1\} - \{10\bar{1}2\}$ twins in a deformed tube from alloy AM30 decreases upon growth in the temperature. The strain hardening index *n* also first grows (below 300°C) and then decreases when the temperature is increased. The data of [8] allow us to infer that the twinning-induced softening is higher than the twinning-induced hardening.

An unusual temperature dependence of quantity *n* for magnesium alloys has been observed in [11] under the conditions when twinning prevailed at moderate temperatures. In our study, as in works [8, 11], the behavior of *n* showed that the softening of cast alloy AZ91 due to twinning exceeded the twinning-induced hardening. However, the random orientation of grains in the cast alloy AZ91 did not allow us to determine with certainty the type of twinning under the deformation [12].

Microstructure

Figure 3 presents the microstructure and the data of an energy dispersive analysis of magnesium alloy AZ91 in cast condition. In accordance with the Mg – Al binary phase diagram [2] the microstructure of a cast alloy is represented by primary crystals of magnesium and an eutectic β-$Mg_{17}Al_{12}$ phase distributed over grain boundaries and between dendrite arms. We established that the mean grain size prior to compression was 280 μm. The particles of the second phase (Fig. 3*a*) are surrounded by a narrow dark region. Judging by the data of the energy dispersive analysis these are particles of $Mg_{17}Al_{12}$ (Fig. 3*b* and *c*).

The microstructure of specimens deformed at a temperature ranging from room one to 150°C is presented in Fig. 4. Deformation at room temperature is accompanied by intense formation of twins (Fig. 4*a*). The grain boundaries and the coarse particles of the second phase can hinder the growth of twins. It can be seen from Fig. 4*b* that after the deformation at 10°C the content of twins in the structure of the alloy decreases and some twins intersect each other. When the deformation temperature is increased to 150°C, the content of twins continues to decrease (Fig. 4*c* – *f*). Fine secondary twins appear inside some large ones.

The complex orientation relations between grains and primary and secondary twins have been studied in detail in [13]. According to this work, the $\{10\bar{1}2\}$ twins detected in primary $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ twins may be described as secondary $\{10\bar{1}1\} - \{10\bar{1}2\}$ and $\{10\bar{1}3\} - \{10\bar{1}2\}$ twins. The driving force of the generation of secondary twins is stress concentration on twin boundaries in the deformation process. The formation of thin secondary twins inside coarse primary ones provides softening of the magnesium alloy. For this reason the strain hardening index *n* at a deformation temperature of 150°C is lower than at 100°C.

Changes in the microstructure of alloy AZ91 after deformation of the same degree at different temperatures are presented in Fig. 5. The main mechanism of straining at 200°C is twinning (Fig. 5*a*). However, many twins bear nuclei of dynamic recrystallization. It can be assumed that the main mechanism of softening at moderate temperatures is dynamic recrystallization through formation of twins. Accord-

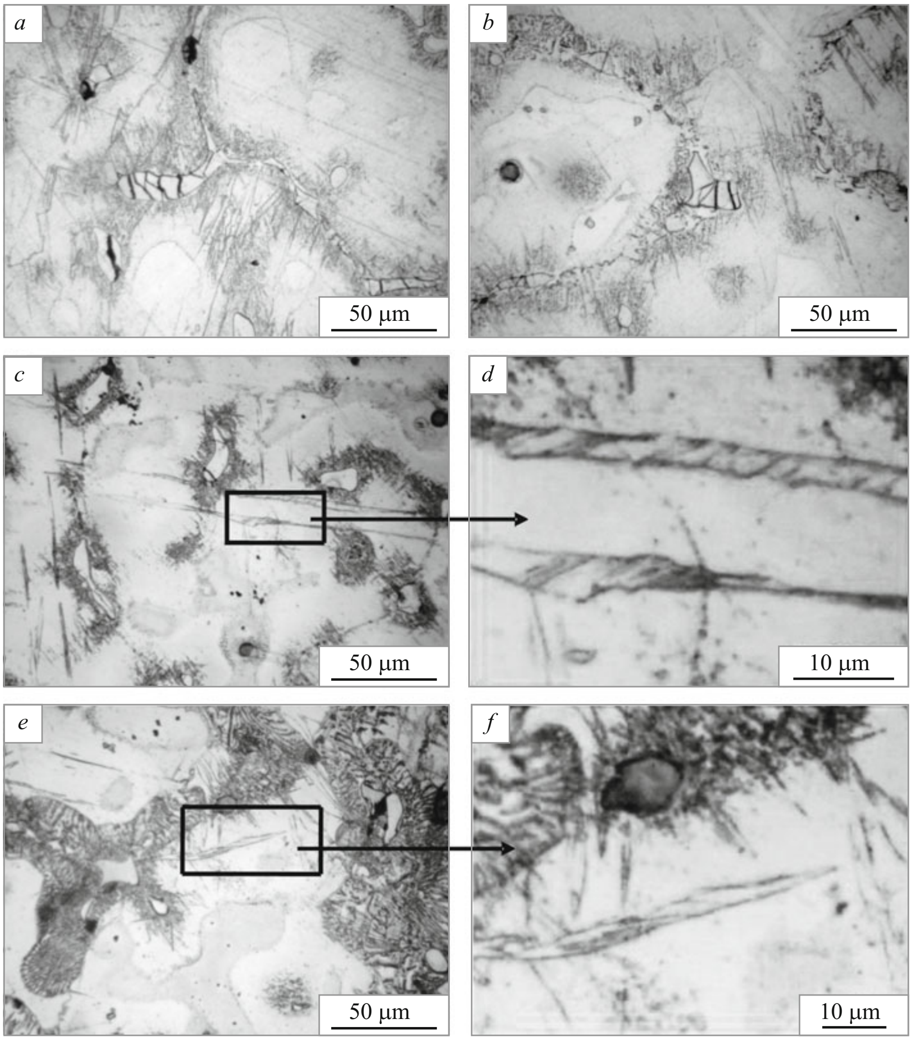


Fig. 4. Microstructure of magnesium alloy AZ91 after deformation at different temperatures: *a*) room temperature; *b*) 100°C; *c* – *f*) 150°C.

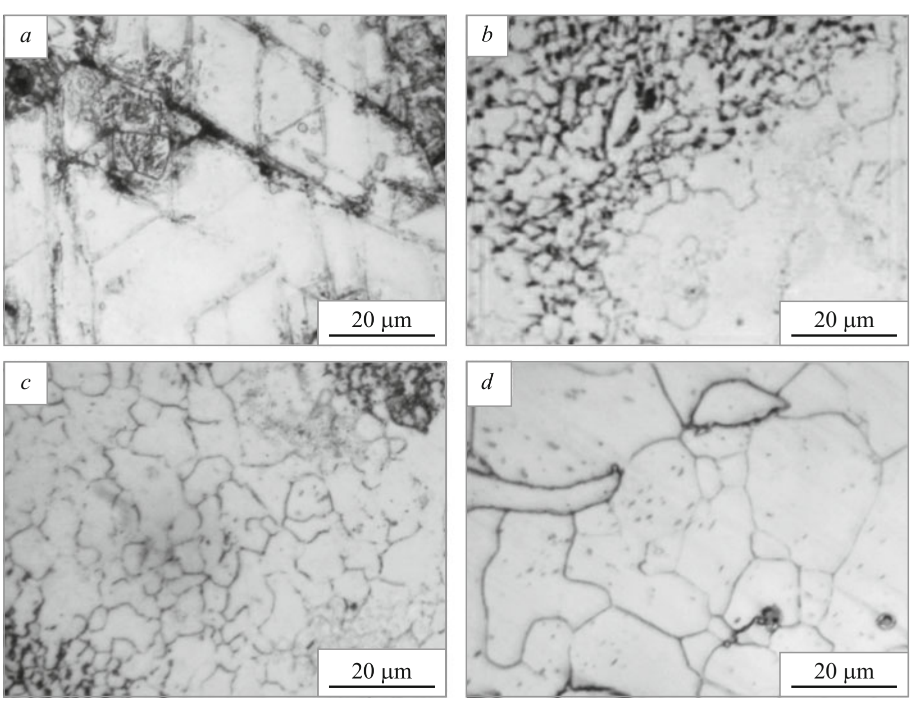


Fig. 5. Microstructure of cast magnesium alloy AZ91 after deformation at different temperatures: *a*) 200°C; *b*) 300°C; *c*) 350°C; *d*) 400°C.

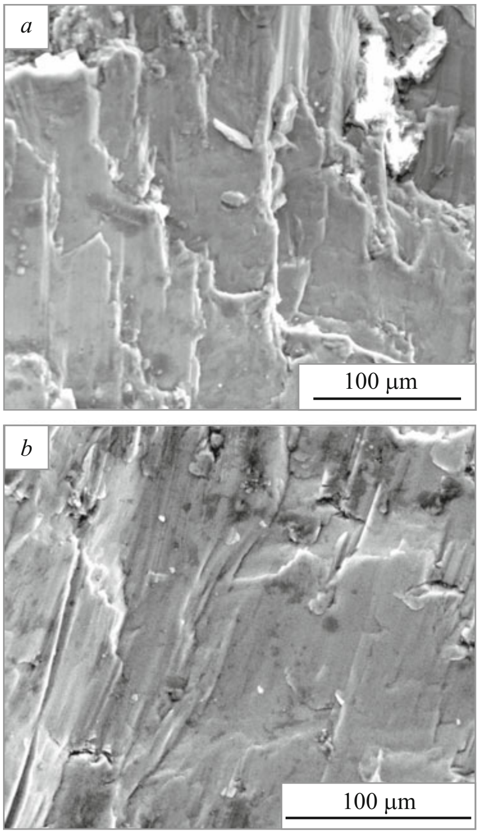


Fig. 6. Fracture surface of a specimen deformed by compression at 100°C (two different regions).

ing to the data of [14], the main mechanism of formation of nuclei of dynamic recrystallization is intersection of secondary twins and primary twins. Consequently, the occurrence of secondary twinning at 150°C may be treated as the initial stage of twinning dynamic recrystallization. When the deformation temperature is increased, the secondary twins located inside primary twins can transform into nuclei of dynamic recrystallization, as it is shown in [13]. Figure 5*b* and *c* present completely dynamically recrystallized grains with a mean size of about 12 μm; twins are absent. Some of the grains are surrounded by extremely small grains (a necklace structure, Fig. 5*b*). This is a typical feature of continuous dynamic recrystallization. We may conclude that when the deformation temperature is increased from 200 to 300°C, the softening mechanism changes; at 300°C twinning stops to be the main mechanism of softening. Further increase of the deformation temperature results in progressive absorption of the ultrafine dynamically recrystallized grains (Fig. 5*c* and *d*).

In the present work, the tests for compression at a deformation rate of 10^{-2} sec^{-1} at a temperature from room one to 150°C resulted in failure of the specimens. At a higher test temperature failure did not occur. Figure 6 presents the fracture surface of a specimen tested at 200°C, in which we can observe shear bands located at an angle of 45° to the compression axis. In [15, 16] the shear fracture of a magnesium alloy under compression is associated with coarse grains.

CONCLUSIONS

1. Twinning is the main mechanism of compressive deformation of cast magnesium alloy AZ91 at a temperature ranging from room one to 200°C. Primary twins are accompanied by a certain number of secondary twins. When the test temperature is increased, the content of twins decreases and the arising dynamic recrystallization produces softening.

2. The strain hardening index *n* passes through a maximum at 100°C depending on the deformation temperature. The decrease in *n* shows that the effect of the twinning-induced softening exceeds the effect of the twinning-induced hardening.

3. Dynamic recrystallization by the twinning mechanism is replaced by continuous dynamic recrystallization upon growth in the deformation temperature.

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