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Deformation Microstructures of Mg-3Al-1Zn Magnesium Alloy Compressed Over Wide Regions of Temperature and Strain Rate

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Hot compression tests of Mg-3Al-1Zn magnesium alloy were performed at temperatures between 300-500 °C and strain rates between 0.03 and 90 s^{-1}. Dynamic recrystallization of the alloy is developed by the necklace mechanism. At the temperature of 300 °C, structures are fully dynamic recrystallized except at intermediate strain rates. As temperature rises to 400 °C, structures are fully recrystallized at all strain rates. The abnormal grain size increase at high strain rate is attributed to the temperature rising of the deforming sample.

Keywords dynamic recrystallization, magnesium alloy, microstructure, necklace mechanism, wrought

1. Introduction

Magnesium alloys have broad application in engineering lies in their low density, high specific strength and high specific stiffness (Ref 1-6). Compared with magnesium casting products, wrought magnesium alloys have so far found very limited usage, although they are expected to have higher strength and ductility than the cast counterparts. One of the barriers to the applications of wrought magnesium alloys is their low workability, as a result of hexagonal crystal structure, often in combination with the presence of phases with low melting points. Therefore, it is necessary to improve the formability of magnesium alloys to fulfill the requirement of industry.

The hot bulk deformation processes (such as extrusion, forging and rolling) are efficient ways to produce fine grain structure, which can result in the simultaneous increase of strength and ductility (Ref 7). The grain size of wrought Mg-products is in the most cases determined by recrystallization, either during or following deformation (Ref 8). The principal variables that affect grain size during hot deformation are (i) deformation temperature, (ii) deformation ratio and (iii) speed of deformation (Ref 9). Uni-axial compression at elevated temperatures is a very elegant way to simulate the hot bulk deformation processes (Ref 10). The bulk of literature which reported on hot compression testing on magnesium alloys concerned relatively low strain rates (0.0001-1 s^{-1}) (Ref 11, 12). However, the strain rates applied in the industrial deformation processes are expected significantly higher. The present study is aimed at discussing the influence of deformation variables to dynamic recrystallization behaviors of Mg-3Al-1Zn magnesium alloy by hot compression in wide regions of temperature and strain rate.

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2. Experimental Procedure

Cylindrical-shaped samples (Φ 10 mm × 12 mm) were cut from a pre-extruded Mg-3Al-1Zn rod by means of spark erosion in a way that the height H was parallel with the direction of extrusion. Hot compression tests were carried out using a Gleeble 3500 machine at a constant strain rate ranging from 0.03 to 90 s^{-1} and at an initial sample temperature ranging from 300 to 500 °C. The specimen was heated to a preset temperature at a rate of 10 °C/s, soaked for 60 s to ensure temperature equilibrium. And then compressed to a height of 4.4 mm, thereby achieving a true strain of 1. All the tests were performed in a vacuum system. The compressed samples were automatic gas quenched immediately upon the completion of the tests. Detailed description of the compression procedure can be found in Ref 13.

The compressed samples were examined on grain structure in the plane which lies in the compression direction. The etchant used to reveal the grains was Acetic-Picric acid (4.2 vol.%). The optical micrographs were taken with an Olympus Microscope BMX60. The average grain sizes were measured by a linear intercept method.

3. Results and Discussion

It is well known that dynamic recrystallization is a diffusion controlled process and consists of nucleation and growth of new grains. Depending on the deformation conditions the nucleation rate can be larger than the growth rate or vice versa.

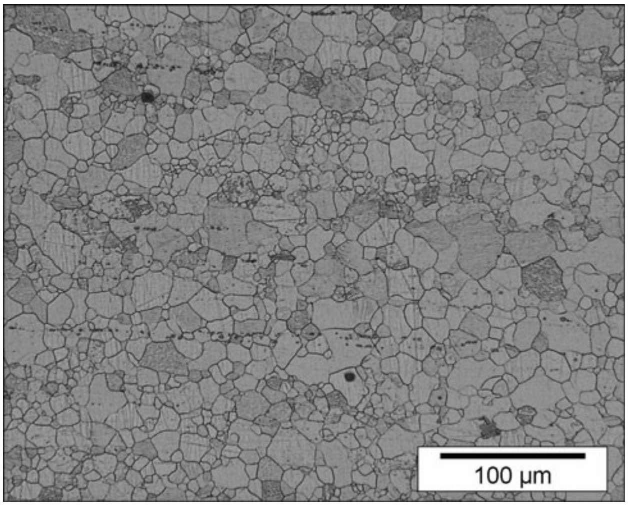

Fig. 1 Grain structure of Mg-3Al-1Zn magnesium alloy before compression, and the extrusion axis was in the horizontal direction

To be more precisely, the resulted grain structures after compression are not only affected by temperature, but also by strain rate.

The microstructure of pre-extruded Mg-3Al-1Zn alloy is shown in Fig. 1, which exhibits a mixed structures of coarse grains and very fine recrystallized grains, this microstructure was produced by partly dynamical recrystallization during extrusion of the coarse-grained ingot.

Figure 2 shows the microstructure of the pre-extruded Mg-3Al-1Zn alloy after compressed at 300 °C. It can be observed that at low strain rate of 0.03 s^{-1} and high strain rates of 30 s^{-1} and 90 s^{-1}, the structures are fully recrystallized. But at intermediate strain rates of 0.3 and 3 s^{-1}, a mixture of initial (old) grains and new grains is presented. In terms of the time and temperature dependency of dynamic recrystallization, lower strain rates provide more time, which are required for the nucleation and growth of dynamically recrystallized grains. However, in the present study, the structures at high strain rates of 30 and 90 s^{-1} also show fully dynamical recrystallization. According to Ref 13, the increase of dynamic recrystallization

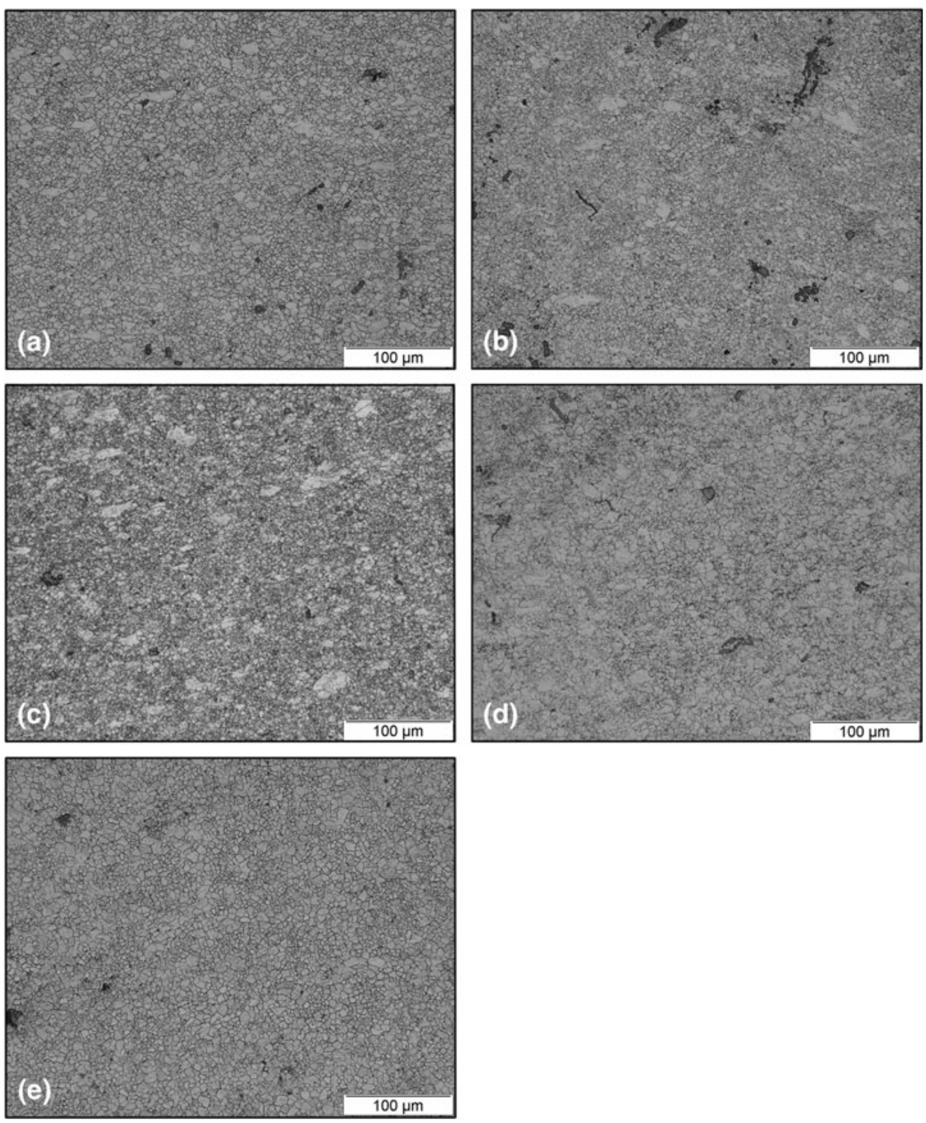

Fig. 2 Grain structures of Mg-3Al-1Zn magnesium alloy after compression at $T = 300$ °C, $\varepsilon = 1$, (a) $\dot{\varepsilon} = 0.03\,s^{-1}$, (b) $\dot{\varepsilon} = 3\,s^{-1}$, (c) $\dot{\varepsilon} = 30\,s^{-1}$, (d) $\dot{\varepsilon} = 90\,s^{-1}$, and compression axis was in the vertical direction

Table 1 The average grain size under various deformation conditions

Strain rate, s^{-1}	Temperature, °C	Average grain size, μm
0.03	300	7.4
0.3	300	7.3
3	300	5.5
30	300	7.8
90	300	9.7
0.03	400	13.6
0.3	400	9.7
3	400	10.7
30	400	10.2
90	400	9.8
0.03	500	19.9
0.3	500	24.9
3	500	30.7
30	500	21.4
90	500	17.6

volume at high strain rates is subjected to the temperature rises of the deforming sample caused by the deformation heating. According to the model developed in reference (Ref 13), the calculated temperature rise of the sample at strain rate of 90 s^{-1} is up to 90 °C at the ending of deformation. The rising temperature of sample benefits the nucleation of dynamic recrystallization and growing of grains. In Fig. 2 and Table 1, it can be found that the average grain size at the strain rate of 90 s^{-1} is greater than that at 30 s^{-1}.

It can be clearly seen in Fig. 3 that when the deformation temperature rises to 400 °C, the structures are fully recrystallized at all strain rates. While dynamic recrystallization is not completed at temperatures as high as 450 °C in the alloy tested by McQueen and Konopleva (Ref 14) and the recrystallized grains still form a mantle. This different behavior can be attributed to the coarse grain size (200 μm) of the alloy tested in reference (Ref 14). Similar to the deformed structures at 300 °C, the grain size at 400 °C decreases with the increasing of strain rate, except at the stain rate of 90 s^{-1} due to the temperature rise

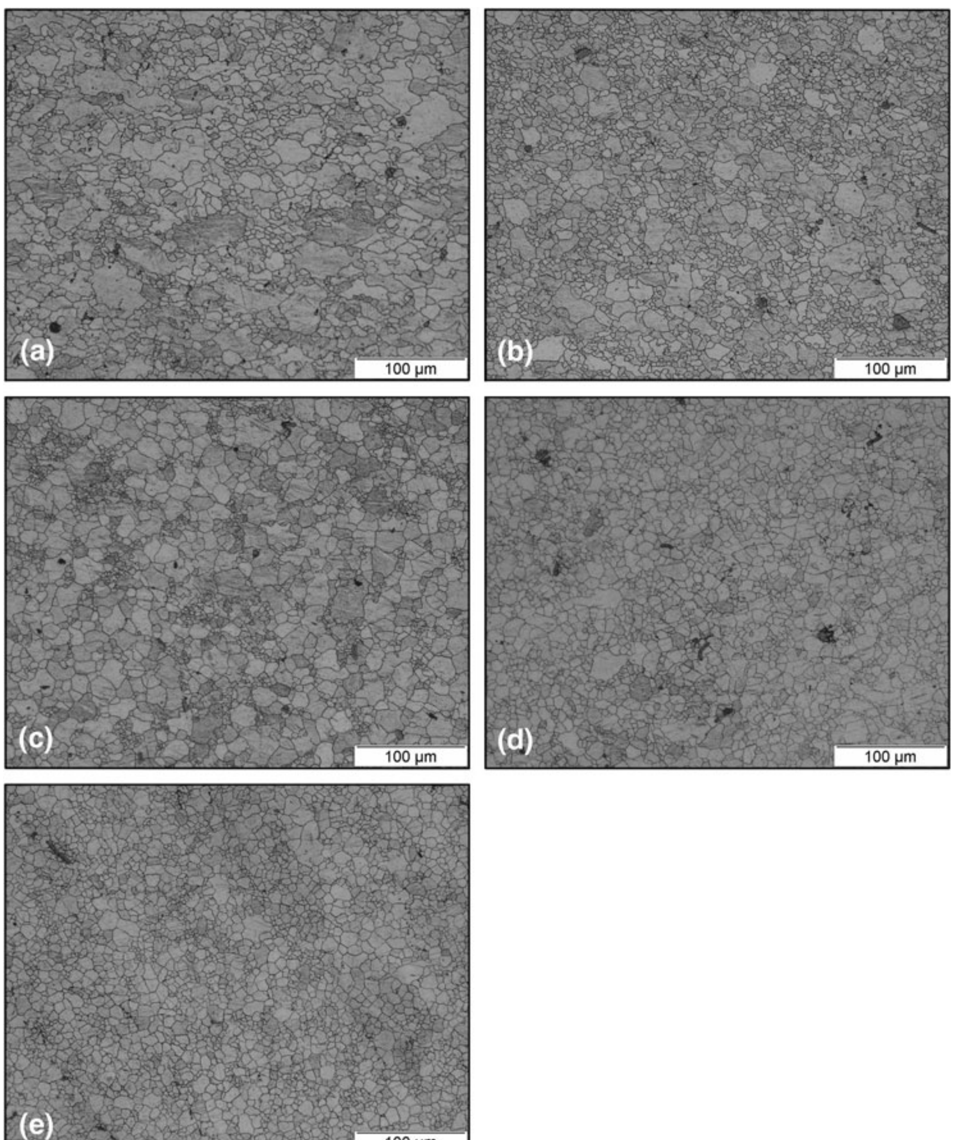

Fig. 3 Grain structures of Mg-3Al-1Zn magnesium alloy after compression at $T = 400$ °C, $\varepsilon = 1$, (a) $\dot{\varepsilon} = 0.03\,s^{-1}$, (b) $\dot{\varepsilon} = 3\,s^{-1}$, (c) $\dot{\varepsilon} = 30\,s^{-1}$, (d) $\dot{\varepsilon} = 90\,s^{-1}$, and compression axis was in the vertical direction

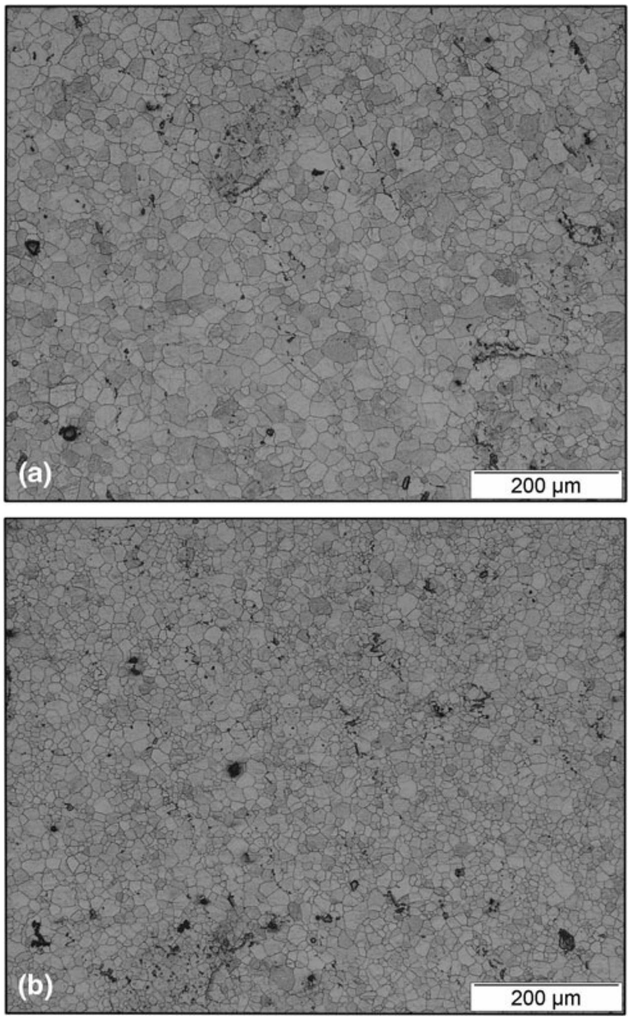

Fig. 4 Grain structures of Mg-3Al-1Zn magnesium alloy after compression at $T = 500$ °C, $\varepsilon = 1$, (a) $\dot{\varepsilon} = 30\,\mathrm{s}^{-1}$, (b) $\dot{\varepsilon} = 90\,\mathrm{s}^{-1}$, and compression axis was in the vertical direction

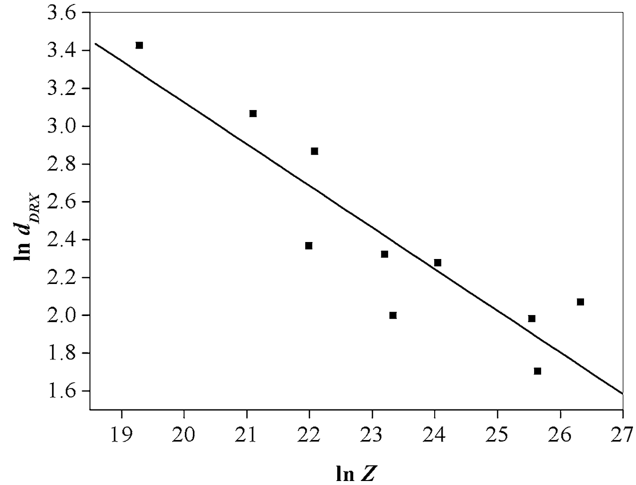

Fig. 5 The relationship between ln d_{DRX} and ln Z of Mg-3Al-1Zn magnesium Mg alloy

of the deforming sample. However, the abnormal grain size increase at the stain rate of 90 s^{-1} was not found when the deformation temperature rises to 500 °C (see Fig. 4). With the increasing of deformation temperature, the flow stress decreases, and the deformation heating and temperature rise of the sample decrease according to (Ref 13). In Fig. 3, it can also be seen that the coarse grain boundaries appeared serrated at low strain rate of 0.03 (Fig. 3a), which is consistent with the finding of other researchers (Ref 15-17). The grain refinement during dynamic recrystallization is insignificant at high temperatures due to the rapid grain growth. In addition, the grain refinement showed a maximum value at a relative low temperature of 300 °C and a high strain rate of 30 s^{-1}.

According to Fig. 2 and 3, the dynamic recrystallized grain size increases with the increasing of deformation temperature and the decreasing of strain rate. The grain size evolution at higher temperatures (400 °C) is more strain rate sensitive than at lower ones (300 °C). According to the time and temperature dependency of dynamic recrystallization, lower strain rates provide more time and higher temperatures provide higher boundary mobility, both of which are also required for the nucleation and growth of dynamically recrystallized grains.

Zener-Hollomon parameter $Z = \dot{\varepsilon}\exp\left(Q/_{RT}\right)$(Ref 18) ($Q$ is activation energy and R is the gas constant) is related to deformation temperature and strain rate. There is a relationship between the average recrystallized grain diameter d_{DRX} and Z-parameter (Ref 12)

$$d_{\mathrm{DRX}} = AZ^{-n} \tag{Eq 1}$$

where d_{DRX} is the average recrystallized grain diameter, n is power law exponent and A is a constant. Equation 1 can be described as:

$$\ln d_{\mathrm{DRX}} = \ln A - n \ln Z \tag{Eq 2}$$

In the present study, the relationship between the average recrystallized grain diameter d_{DRX} and Z-parameter can be described as $d_{\mathrm{DRX}} = 1864.653 \times Z^{-0.221}$ (see Fig. 5). It shows that the recrystallized grain diameter d_{DRX} decreases with increasing value of Z-parameter.

Figure 6 shows the evolution of recrystallized microstructures during the deformation process. At the beginning of the deformation process ($\varepsilon = 0.2$), as shown in Fig. 6(a), recrystallization microstructure develops as a necklace structure originating at the prior grain boundaries and progressively consuming the interior of the deformed grains. From Fig. 7, it can be concluded that dynamic recrystallization initiated after the peak stress, and can be clearly identified as point (c). The observation is also agreed well with the finding of reference (Ref 15). When the strain increases to 0.5 (Fig. 6b), second layers of the necklace structure start to form. The amount of fine dynamically recrystallized grains increases greatly. A gradual decrease in flow stress could be observed when deformation proceeded from $\varepsilon = 0.2$ to $\varepsilon = 0.5$ (Fig. 7). The strain softening behavior is attributed to the absorption of dislocations in the boundary during the dynamic recrystallization process. When $\varepsilon = 1$, dynamic recrystallized grains almost cover the entire microstructure (see Fig. 6c). The flow stress exhibits a steady state from $\varepsilon = 1$ to $\varepsilon = 1.2$.

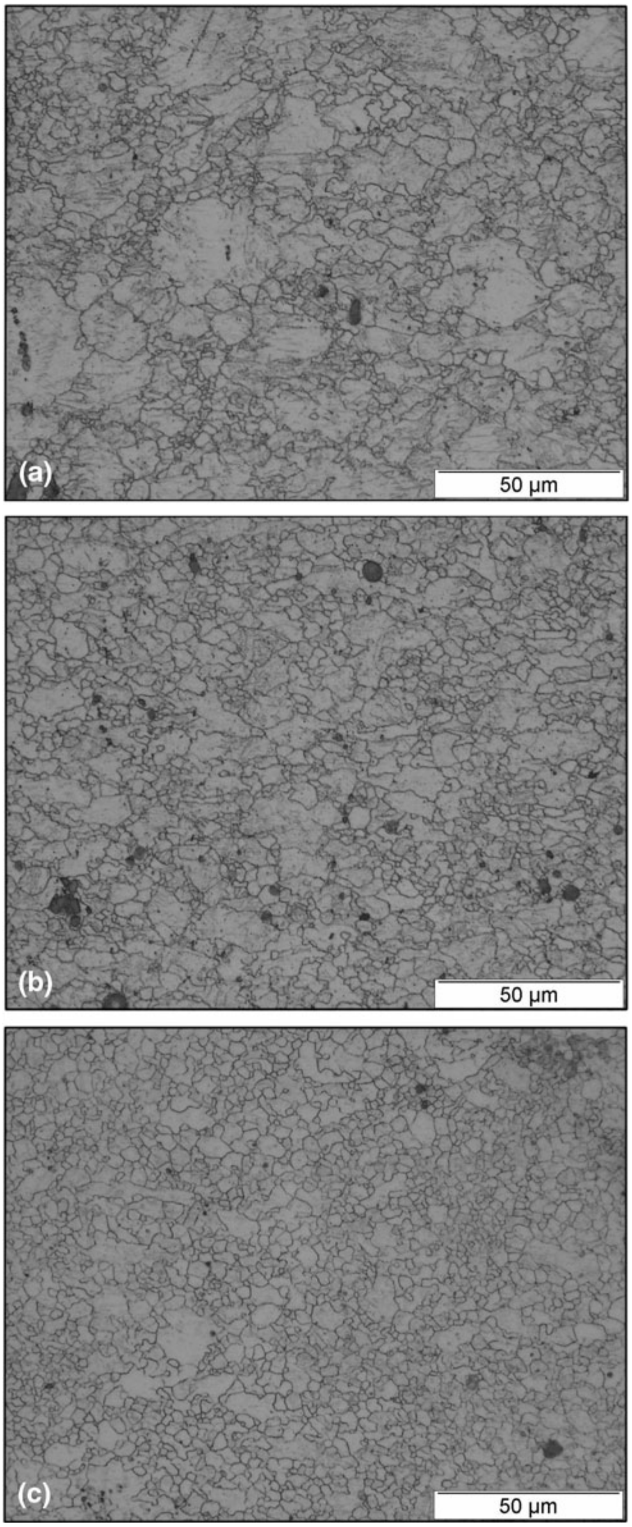

Fig. 6 Grain structures of Mg-3Al-1Zn magnesium alloy after compression at 300 °C and 0.3 s^{-1}, (a) ε = 0.2, (b) ε = 0.5, (c) ε = 1, and compression axis was in the vertical direction

4. Conclusions

1. The dynamic recrystallization of the Mg-3Al-1Zn magnesium alloy was nucleated and developed by strain induced grain boundary migration and by the necklace mechanism.

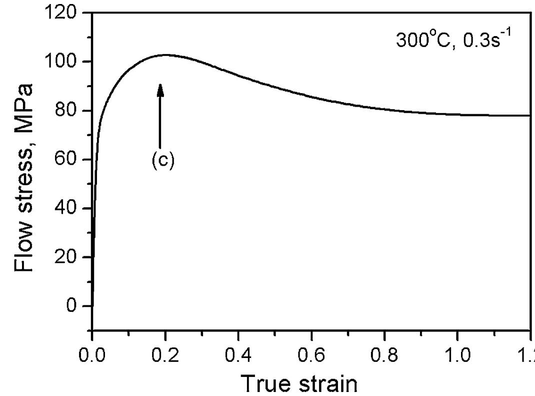

Fig. 7 True stress vs. true strain curve at 300 °C and 0.3 s^{-1}

2. At the deformation temperature of 300 °C, structures are fully dynamic recrystallized except at intermediate strain rates of 0.3 and 3 s^{-1}. As temperatures higher than 400 °C, structures are fully recrystallized at all strain rates.
3. Dynamic recrystallized grain size increases with the increase strain rate and the decrease of deformation temperature. The grain size evolution at higher temperatures is more strain rate sensitive than at lower ones.
4. At the deformation temperature of 300 and 400 °C, there is an abnormal grain size increase at the strain rate of 90 s^{-1}, which is attributed to the temperature rise of the deforming sample caused by deformation heating.

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