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Influence of a weak pulsed magnetic field on the recovery and recrystallization in aluminum

A. Brusov, M. Azoulay, G. Orr, G. Golan*

Ariel University, Science Park, Ariel 40700, Israel

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Pulsed Magnetic Field (PMF) is an easy and effective method for changing the properties of various materials. In this work we present the influence of a weak pulsed magnetic field (WPMF) on the recovery and recrystallization processes in 99.99% aluminum. The state of the material before and after processing was determined by the method of Internal Friction (IF). It was found that if WPMF is carried out simultaneously with heating and annealing of deformed aluminum, then the recrystallization process is observed at lower temperatures. Pre-treatment with WPMF for 72 hours before annealing reduces the height of the IF peak and causes a more intense decrease in the level of IF at temperatures of 350°-400°C. Thus, the aftereffect of the WPMF during the recrystallization of deformed aluminum can be monitored.

Keywords: aluminum, weak pulsed magnetic field, internal friction, recovery, polygonization, recrystallization

INTRODUCTION

In recent years, interest has grown in processing with pulsed magnetic fields, as it is an easy and effective method for changing the properties of various materials, including non-magnetic ones. Of particular interest is the use of processing pulsed fields in the range of treatment with weak magnetic pulses ($H<10^6$ A/m) or the so-called weak "magnetic field processing" (MFP). Magnetoplastic effect in non-magnetic crystals, internal friction and the effect of constant magnetic field on mechanical properties and dislocation structure of Nb and Mo are detailed in [1, 2] originated the topic on weak pulsed fields. This topic clarified the issue of the effectiveness of the impact of such magnetic treatment on non-magnetic materials. Subsequent studies [3-5] are in good agreement with this concept. It is known that MFP changes the state of impurity–defect complexes on dislocations, and therefore affects materials that are in an unstable transition state and can change properties that depend on the dislocation structure. MFP affects the processes of microplastic deformation, irreversible temper brittleness, and strain aging [6]. Aluminum is used as a substitute for more expensive metals, and the possibility of its use in various applications increases every year. A feature of aluminum (as a metal with a high energy of stacking faults) exhibits the tendency to creep dislocations, and facilitates the formation of structural defect complexes. As a result, there is a strong dependence of its plastic and strength properties on the dislocation structure. Therefore, it can be assumed that treatment with a weak pulsed magnetic field will be effective when exposed to aluminum under conditions of a change in the dislocation structure during the processes of recovery, polygonization, and recrystallization. The method of internal friction (IF) was used, as the most sensitive one in the study of structure-dependent properties. Kong and Fang [7] observed a relaxation peak of internal friction on pure polycrystalline aluminum with a maximum temperature of 280°C at a frequency of 1 Hz. They showed that this peak is attributed to grain boundary, since it could not be found in single-crystal aluminum. The torsion pendulum method was used to detect bismaleimide triazine (BT) peaks on copper, iron, manganese, bismuth, and other metals. It was believed that they have a grain-boundary nature and are associated with viscous intergranular slip. Later, Woirgard discovered IF peaks on deformed single crystal metals using the low-frequency flexural vibration method. The appearance of these peaks was associated with the glide of dislocations. According to a later representation [7], the IF peak was found to consist of at least two components, low- and high-temperature components. Despite the fact that the solution of this issue continues to be relevant [7], all researchers agree that internal friction is a very sensitive indicator for changes in the dislocation structure of a material. The method of internal friction can predict the interaction of vacancies, impurity atoms and dislocations. Also, it can predict the processes of formation of impurity defect complexes (IDCs) on dislocations. Therefore, in the current work, it was found that this method is useful to study the effect of WPMF on the dynamics of structural rearrangement of aluminum during processes of recovery, polygonization, and recrystallization, as well as the effect of magnetic

* To whom all correspondence should be sent:
E-mail: gadygolan@gmail.com

treatment on low-temperature peaks at 80°C, 150°C and the Ke peak.

MATERIALS AND PROCESSING

The object of the study was 99.99% aluminum, details are shown below in Table 1. Samples of 3×3×25 mm were deformed by tension of 10%.

Table 1. Residual impurities in 99.99% aluminum

Al	Fe	Si	Mn	Zn	As	N
base	0.006	0.002	0.001	0.0004	0.0002	0.0005

The internal friction was studied on a low-frequency apparatus of the inverted torsion pendulum type. The scheme of the setup is shown in Fig. 1. This laboratory setup makes it possible to simultaneously carry out magnetic processing and heat treatment, such as annealing, hardening, tempering, and to measure internal friction during the entire process. The setup consists of three main elements: 1 - installation for measuring internal friction of the type of reverse torsion pendulum with low oscillation frequencies of 0.5-1 Hz; 2- magnetic solenoids (6 in diagram) which are connected to the installation for processing with magnetic field pulses; 3- heating furnace (5 in diagram).

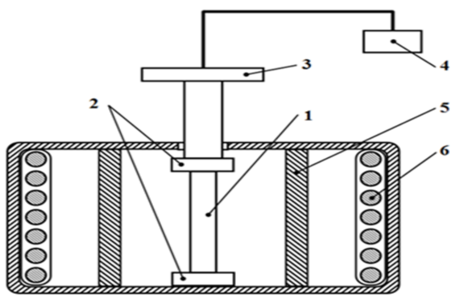


Fig. 1. Setup to study the effect of a pulsed magnetic field on a material, simultaneously with heat treatment. 1-sample; 2- clamps; 3-inertial detail; 4–counterweight; 5-heating chamber; 6-magnetic solenoid.

The processing parameters of the pulsed magnetic field were: magnetic field amplitude $H=3 \cdot 10^5$A/m, pulse repetition rate 0.5 Hz, pulse leading edge duration 10^{-4} s.

The study of the effect of a pulsed magnetic field on the recovery process was carried out at an annealing temperature of 100°C. The deformed aluminum specimens were rapidly heated (6-7 min) from room temperature to 100°C and then kept at this temperature for 1 hour. The influence of the magnetic field was studied directly during heating, annealing, and IF (internal friction) measurements. To study the processes of polygonization and recrystallization, the deformed samples were heated at a rate of 4 °C/min to annealing temperatures, kept for 40 minutes, and slowly cooled at a rate of 15 °C/h to room temperature. The annealing temperature was varied from 200°C to 600°C with an interval of 100 °C. The aftereffect was studied in the following way: aluminum was treated with magnetic field pulses for 5 minutes at room temperature, then the samples were kept for 3 days, after which they were annealed, and the IF was measured. We studied the temperature dependence of the internal friction at relative strain amplitude of the material $\varepsilon = 2\times10^{-5}$. The measurement error did not exceed 10%.

RESULTS AND DISCUSSION

The temperature dependence of the internal friction of aluminum with and without magnetic field treatment during the recovery process is shown in Fig. 2.

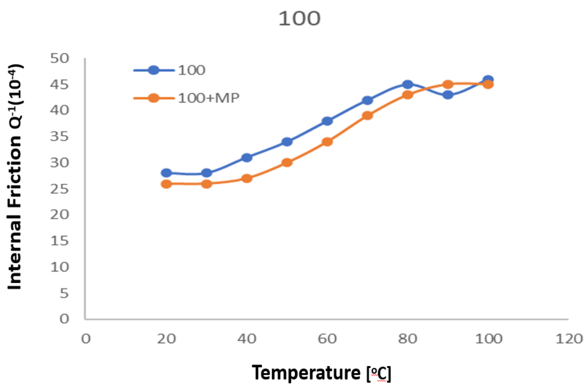
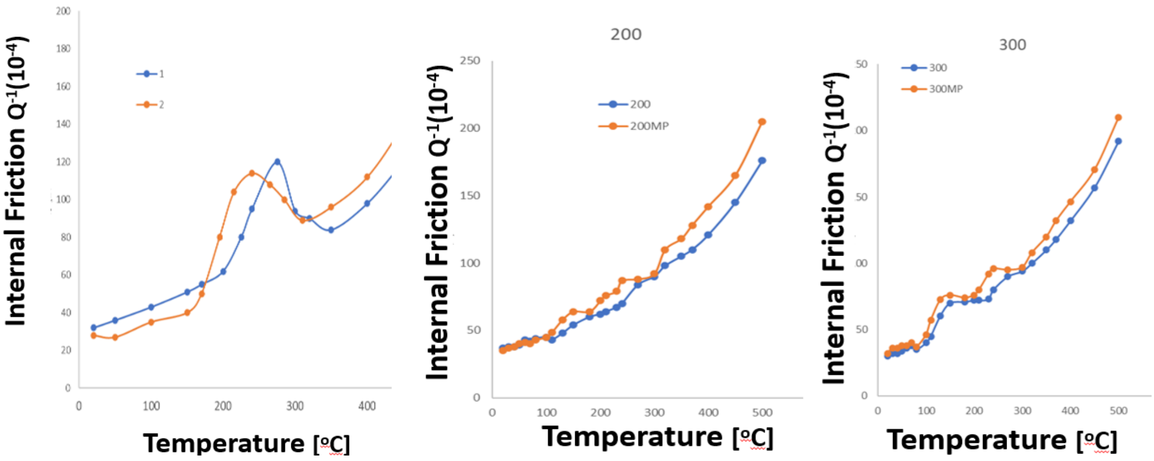


Fig. 2. Temperature dependence of internal friction in aluminum (purity 99.99%) during annealing at a temperature of 100 °C: 1-without a pulsed magnetic field; 2-with a pulsed magnetic field.

The results of studying the temperature dependences of IF show that under normal conditions of sample heating in the return temperature range, there is a monotonous increase in the level of IF. A slight increase in IF value is observed around 80 °C. This small peak flattens out after MFP treatment, while the background level of IF is somewhat lower than the level without treatment.

The effect of MFP on recrystallization and polygonization processes was studied on samples that were annealed as described previously. Then the samples were mounted in a setup and heated to a temperature of 500°C at a rate of 25 °C/h. IF was measured without WPMF treatment and with treatment by heating at intervals of 10°C to a temperature of 110°C, at intervals of 20°C to a temperature of 400°C, and at intervals of 50°C to a temperature of 500°C. The results obtained are presented in Figs. 3-6.



A B C

Fig. 3. Temperature dependence of internal friction in aluminum (purity 99.99%): A-deformation 10% without annealing; annealing at temperature: B-200° C; C -300°C. Curve 1 - without pulsed magnetic field; curve 2 - in a pulsed magnetic field.

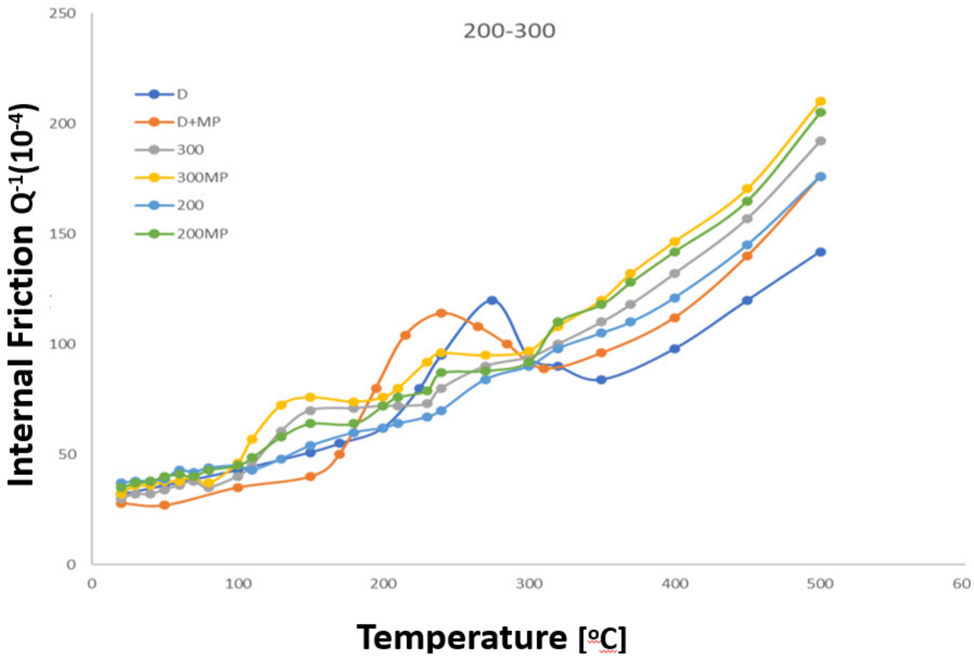
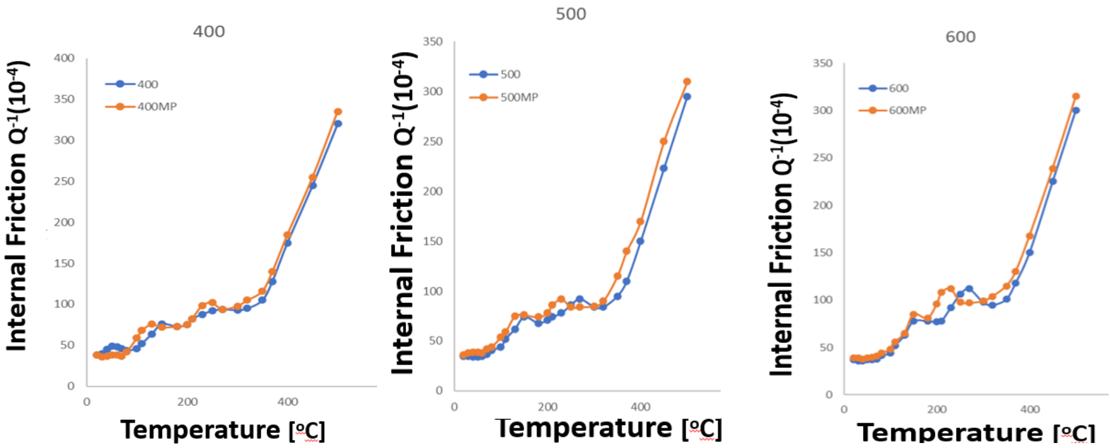


Fig. 4. Summary graph of temperature dependences of internal friction after: D - 10% deformation without annealing, after annealing 200°C and 300°C. Lines 200 and 300 without pulsed magnetic field; D+ MP, 200MP, 300MP - in a pulsed magnetic field.

Peak Ke, located in the region of 270°C, is the highest one and has the largest half-width after deformation, but after annealing at 200°C, it practically disappears (Fig. 4). This peak becomes very small in the curve after annealing at 300°C. After annealing at 300°C, another peak appears around 150°C (Fig. 3c, curve 1). This peak is associated with lattice dislocations. After annealing at 200°C without PMF treatment, no peaks are observed (Fig. 3b, curve 1). MFP treatment affects the processes of structural rearrangement during annealing of deformed aluminum, which is confirmed by changes in the temperature dependences of IF. All types of peaks are shifted to lower temperatures by about 30°C, after pulsed magnetic treatment (Fig. 3). Also, after MFP treatment, small peaks appear on the curves after annealing at 200°C (Fig. 3b, curve 2) at the same temperatures, namely 150°C and 240°C, as during annealing in a magnetic field at 300°C.



A B C

Fig. 5. Temperature dependence of internal friction in aluminum (purity 99.99%) after annealing at temperature: A-400°C; B –500°C; C-600°C. Curve 1 - without pulsed magnetic field; curve 2 - in a pulsed magnetic field.

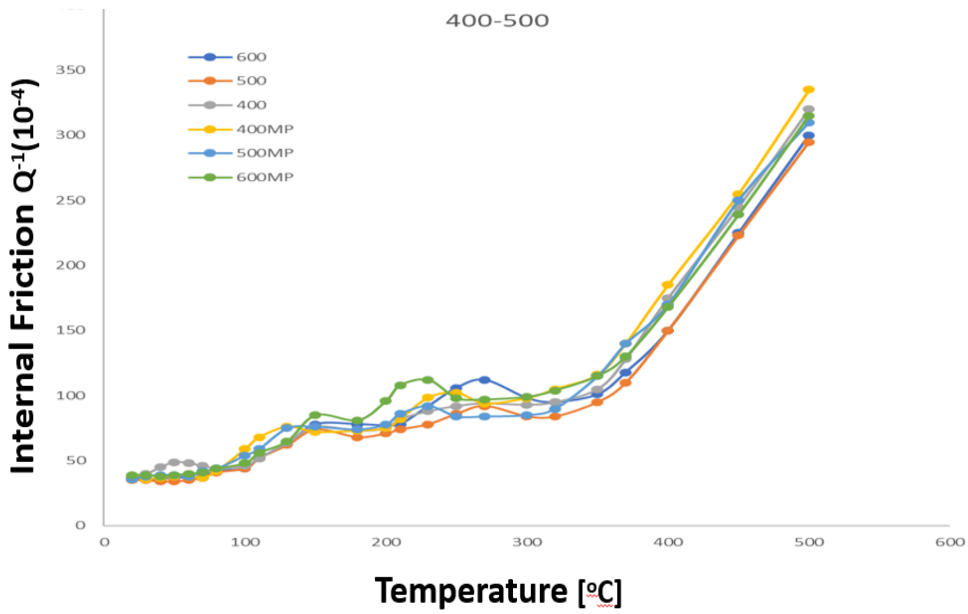


Fig. 6. Summary graph of temperature dependences of internal friction after deformation of 10% and annealing at temperatures of 400°, 500°C, and 600°C. Curves 400, 500, and 600 without pulsed magnetic field; curves 400MP, 500MP, 600MP - in a pulsed magnetic field.

The temperature dependences of IF during further annealing at higher temperatures are shown in the graphs 5-6. Peak Ke (270°C) is clearly seen after annealing at 400°C, gradually increasing with the annealing temperature and strongly increasing at annealing at 600°C (Fig. 6, curves 400, 500, 600). However, the height of the main peak does not restore its original value before deformation. The peak at 150°C, which appeared after annealing at 300°C, slightly increases with increasing annealing temperature. Treatment in a pulsed magnetic field leads to a shift of the Ke peak by approximately 25–35°C to lower temperatures, while the peak height remains approximately at the same level; this trend is typical for all annealed states. The low-temperature peak (150°C) also shifts towards low temperatures by 20-30 degrees (curve 2 in Figs. 5 a, b, c). The results of the study of the aftereffect are presented in Fig. 7.

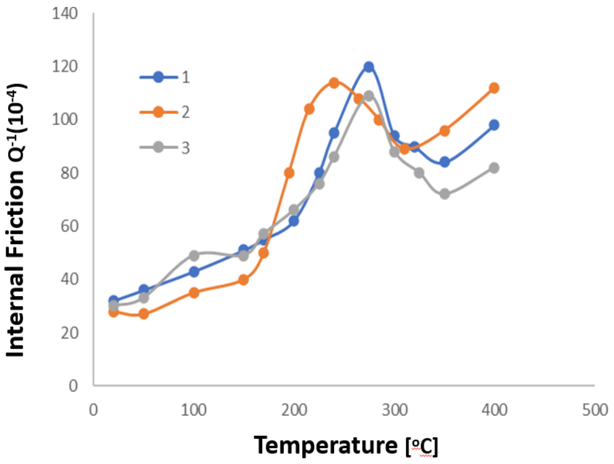


Fig. 7. Temperature dependence of the internal friction in deformed aluminum with a purity (99.99%): 1- without a pulsed magnetic field; 2- in a pulsed magnetic field; 3- aftereffect of the magnetic field.

On the curve with MFP aftereffect (Fig. 7, curve 3), a slight decrease in the IF peak is observed, but in general, this curve coincides with the curve without MFP. The decrease in the level of internal friction on the aftereffect curve at temperatures of 350°–400°C occurs more intensively than on the other two curves. The data obtained confirm the possibility of the influence of a weak pulsed magnetic field on the processes of structural rearrangement during the processes of polygonization and recrystallization of deformed polycrystalline aluminum with a purity of 99.99 (annealing at 200°-600°C). The processes of change in the dislocation structure, which are characteristic of polygonization and recrystallization, proceed more intensively and begin earlier under the influence of MFP. This corresponds to the fact that the MFP treatment, acting on the dislocation system - impurity-defect complexes, leads to a decrease in the activation energy of grain-boundary relaxation, a decrease in the dislocation density and a shift of the Ke peak to lower temperatures. The effect of MFP on the recovery process on the temperature dependences is not significant (annealing at 100°C).

The observed changes in the nature of the peaks at 150°C confirm that these peaks are associated with dislocation relaxation, which also proceeds more actively and begins at lower temperatures under the action of magnetic fields.

CONCLUSIONS

From the above results it can be deduced that the exposure to a weak pulsed magnetic field simultaneously with heating and annealing leads to a shift of the grain boundary peak of IF by 20-30°C lower, that is, it accelerates the processes of structural rearrangement occurring during polygonization and recrystallization, which begin at lower temperatures. Moreover, the aftereffect of the MFP (the effect of magnetic treatment on the material before heating and tempering) is manifested by a decrease in the height of the peak of internal friction and a more intense decrease in the IF level at temperatures of 350°- 400°C. It is also printed out that the MFP affects low-temperature IF peaks (150°C) which are caused by lattice dislocations. This means that the magnetic field affects not only the grain boundary relaxation but also the dislocation relaxation, while the dislocation relaxation behaves similarly to the grain boundary relaxation.

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