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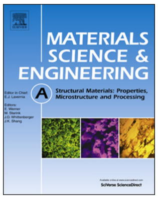

Electromagnetic forming facilitates the transition of deformation mechanism in 5052 aluminum alloy

Ning Li [a,*], Haiping Yu [b], Zhu Xu [a], Zhisong Fan [b], Lin Liu [a]

[a] School of Materials Science and Engineering and State Key Laboratory of Material Processing and Die & Mould Technology, Huazhong University of Science and Technology, 430074 Wuhan, People's Republic of China
[b] School of Materials Science and Engineering, Harbin Institute of Technology, 150001 Harbin, People's Republic of China

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ABSTRACT

The identification of different deformation mechanisms in aluminum alloy under high-velocity electromagnetic forming and mechanical forming is a daunting task, due to the limitations in performing identical experimental conditions. Here, we present a special strategy to achieve electromagnetic and mechanical deformations with equivalent strain and strain rate. The intriguing finding is that the deformation mechanism of 5052 aluminum alloy is dominated by planar slip in mechanical deformation *versus* wavy slip in electromagnetic forming. The physical origin of the phenomenon is rationalized according to theoretical analysis coupled with finite-element-method simulation. The finite-element-method simulation presents planar and spatial force in the aluminum alloy during mechanical deformation and electromagnetic forming, respectively. The theoretical analysis reveals that under mechanical deformation with planar force, the destruction of short range cluster on the activate glide planes reduces the local resistance of dislocation motion and facilitates the planar slip. By contrast, the collective motion of dislocations in three dimensions caused by spatial force under electromagnetic forming facilitates the wavy slip that is represented by the dislocation cell structures. Our findings provide an effective method and fundamental understanding for unveiling various deformation mechanisms in aluminum alloy under electromagnetic and mechanical processing.

1. Introduction

Among metal forming techniques, electromagnetic forming (EMF) is an impulse or high-speed forming technology that utilizes electromagnetic force (*i.e.*, Lorentz force) to shape metal workpieces [1]. The electromagnetic forming has attracted increasing attention in past decades because of its superiority over conventional mechanical forming techniques. The advantages of electromagnetic forming include contact-free forming without a working medium, low springback, high repeatability, high production rates, and enhanced forming limit [1–6], which altogether make electromagnetic forming a powerful toolbox in various industries, especially in the fields of automobile, heavy vehicle, aerospace and electronics [5].

Due to the high strain rate and the electromagnetic force characteristics, the microstructural evolution in electromagnetically formed materials differs significantly from that in materials, which undergo quasi-static or low strain rate deformation. In austenitic stainless steel, for example, the high strain rate electromagnetic forming can induce the formation of stacking faults and twin structures, due to an easier nucleation of partial dislocations and the suppression of α'-martensite ascribable to the adiabatic heating produced during electromagnetic forming [7]. In 5052 aluminum alloy, the electromagnetic forming facilitates the dense dislocation configurations that promote conspicuously the plastic strain [8,9]. In addition to the effect of alloy system, the microstructural evolution in metallic materials under electromagnetic forming is also strain dependent. With an increasing plastic strain, the dislocations in pure aluminum initially increase in density, followed by dislocation localizations which form tangles into cell structures with different cell wall thicknesses until sub-grains finally emerge [10], and the increase of dislocation density results in the reduction of dislocation cell size [11]. The increase of plastic strain also induces textural evolution from Rotated Cube towards Cube and Goss & Rotated Goss in pure aluminum under electromagnetic forming, accompanied with intra-granular misorientations [6]. It is evident that these findings are enormously important because some microstructural evolutions during electromagnetic forming can impose dramatic effects

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* Corresponding author.
E-mail address: hslining@mail.hust.edu.cn (N. Li).

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on component's properties. Especially, multi-turn coils can be designed to form some special parts of the component to adjust the microstructures and to meet the requirement of properties.

The microstructural evolution of metallic materials during mechanical high-speed forming has also been widely investigated. The mechanical twinning, dislocation slipping and adiabatic shear banding are regarded as the three dominant deformation mechanisms for metals under high strain rate deformation [12,13]. The deformation twins that have been well identified in body-centered cubically (*b.c.c.*) and hexagonally close-packed (*h.c.p.*) metals/alloys because of the low stacking fault energy (SFE) or lack of sufficient independent slip systems [14–17]. In recent years, with the assistance of high strain rates, deformation twins were also observed in many face-centered cubic (*f.c.c.*) crystal structure metals and alloys, respectively [18,19], or even in aluminum and aluminum alloys with high stacking fault energy (SFE) due to the effect of high strain rate [14]. High strain rate was also found to induce low dislocation cell size and high dislocation density [20–22]. Furthermore, adiabatic temperature rise may occur in a narrow region under high strain rate deformation and cause the well-known adiabatic shear banding [23,24]. In some case, the local high temperatures and rapid quenching from the cool surrounding result in the occurrence of recrystallization and/or the generation of amorphous phases [13,25–27].

The questions arise as for whether there are differences in microstructural evolution of metallic materials under electromagnetic forming and mechanical high-speed forming, and if yes, what is the underlying origin for this? Direct experimental examination has being very challenging and hence has been rarely performed. To address this issue, we designed a special experiment to investigate the deformation mechanism of a 5052 aluminum alloy under electromagnetic and mechanical forming, respectively. The results suggest that the deformation mechanism is dominated by planar slip under the high velocity mechanical loading (*i.e.* the aluminum alloy is deformed mechanically by copper sheet). In contrast, the deformation is governed by wavy slip as the specimen undergoes an electromagnetic force. Our findings provide an insight into understanding the deformation mechanism of *f.c.c.* aluminum alloys under electromagnetic forming and mechanical processing, respectively.

2. Experimental procedure

2.1. Electromagnetic and mechanical deformations

The 3.0 mm thick 5052 (graded as 5A02 in China) aluminum alloy sheet in a recrystallized condition (annealing temperature: 400 °C) provided by the Southwest Aluminum Company (China) was used in this work. The nominal chemical composition (wt%) of the alloy is listed in Table 1 [28,29]. It is notable that Mg, Si and Fe are the solute atoms in the aluminum alloy.

The 5052 aluminum alloy specimens with a dumbbell shape used for electromagnetic and mechanical deformations were fabricated by wire-cutting from the as-received plates. The experiments were performed on the self-build electromagnetic forming system (EMF30/5/-IV) at Harbin Institute of Technology. The system consists of 14 × 192 μF-capacitors and the charging voltage is 5 kV, which provides a total energy storage of about 33.6 kJ. The rectangular flat spiral coil was designed to provide a homogeneous electromagnetic force [30], as described in Fig. 1(a). Fig. 1(b) schematically illustrates how the electromagnetic deformation was carried out. The current pulse is generated through the work coil (*i.e.* rectangular flat spiral coil) by rapidly discharging the capacitor bank using a switch, creating a rapidly oscillating electromagnetic field around the work coil, which induces a circulating electrical current within a nearby conductor (*i.e.* aluminum alloy) through electromagnetic induction. The induced current creates a corresponding magnetic field around the conductor, and generates electromagnetic forces within the conductor and the work coil. The electromagnetic forces strongly repel each other due to the Lenz's Law and hence deform the metal workpiece [31].

Table 1
Nominal chemical composition of 5052 aluminum alloy (in weight percent,%).

Si	Fe	Cu	Mn	Mg	Ti	Al
0.40	0.4	0.1	0.15–0.40	2.0–2.8	0.15	Balance

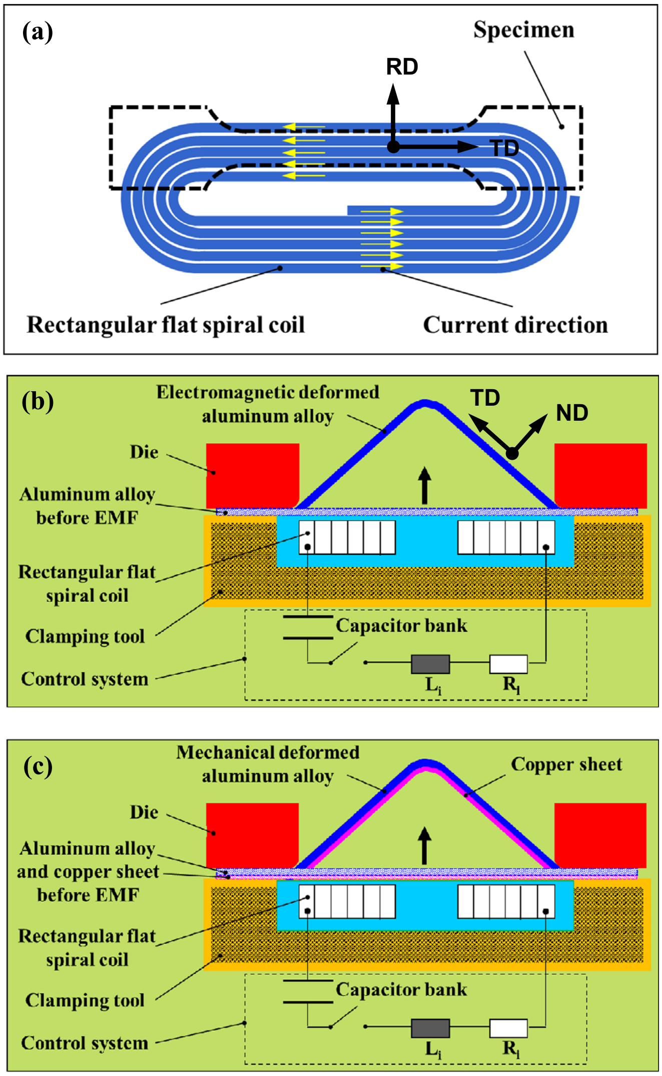

Fig. 1. The sketch of the specimen placed on the rectangular flat spiral coil (a); the schematic diagrams under electromagnetic (b) and mechanical (c) deformations.

In order to achieve the mechanical deformation with an identical plastic strain as used in electromagnetic forming, a copper sheet (with exactly the identical shape of the aluminum alloy specimens) with thickness of 1 mm was placed between the coil and the aluminum alloy, as depicted in Fig. 1(c). In this case, the copper is driven by electromagnetic force, and the aluminum alloy is deformed mechanically by the copper sheet. In the present experiments, a discharging voltage of 2.65 kV was applied in electromagnetic forming, and a relatively large voltage of 3.20 kV was used in mechanical deformation to overcome the resistance of copper deformation and to obtain the identical plastic stain.