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Review

The microstructure and property variations of metals induced by electric current treatment: A review

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ABSTRACT

Heat treatment has been widely applied for manipulating the microstructure and properties of metals with thermal energy. The thermal energy triggers the atomic diffusion accompanied by dislocation movement and results in the subsequent property variations in metals. One of the attractive efforts in the past decades is the development of a direct treatment of metals with electric current stressing as an alternative method for conventional heat treatment. Electric current treatment provides thermal energy from Joule heat (thermal effect) and kinetic energy from electron momentum (athermal effect). This article reviewed the practices of electric current treatment, microstructure-property variations and the physical metallurgy involved in a variety of metals. Both thermal and athermal effects have been well recognized in the literatures. An appropriate manipulation of the electric current treatment enables the control of both effects and thus the microstructure and properties of metals.

1. Background: Conventional Heat Treatment and Electric Current Treatment

Properties of materials are closely correlated with the microstructures. Microstructures of metals can be manipulated by hard working incorporated with the following heat treatments, such as sequential homogenization and annealing processes. The microstructural variations generally occur through the recovery and recrystallization of the metal matrices [1] which eliminate the dislocations produced by hard working. The recrystallization forms strain-free equiaxed grains. The thermal energy provided from heat treatment activated the recovery and recrystallization processes.

The heat treatment is generally conducted in a thermal furnace which provides the heat (thermal energy) in need through conduction or radiation. However, the conventional heat treatment using a thermal furnace takes long time and is a rather energy-consuming process. In addition, the heat treatment process is not an energy efficient process which may involve a large energy loss during the prolonged heating and cooling procedures. It is always desirable to improve the process and energy efficiency of the microstructure and property manipulations.

The direct treatment of metals with electric current stressing as an alternative method for the conventional heat treatment has been disclosed in the literatures. The effects of electric current treatment are twofold: (i) the Joule heat resulting from the intrinsic electrical resistivity of metal conductors contributes the thermal energy, and (ii) the high density electric current carries high momentum electrons resulting in atomic migration known as "electromigration".

In the 1970's to 1980's, Conrad and his group reported a series of studies on the electroplastic and recrystallization in pure metal wires using electropulsing treatment [2–7]. The electropulsing treatment could manipulate the microstructures and mechanical properties by altering the recrystallization kinetics. Ever since then, many attempts have been made for manipulating the microstructures and mechanical properties of a variety of metals with electric current treatment (see Table 1 for details). For example, the electroplastic effect has been applied in cold-rolled 5052-H32 Al alloys to improve the formability of the alloys [21]. The treatments of metals as investigated generally involved a hard working pre-treatment incorporated with the following imposition of electropulsing or alternating current [5–29]. The effectiveness of the methods using electropulsing or alternating current treatment for the microstructure and property manipulation is affected by the dislocations produced. Recent studies have revealed the possibility of a non-deformation direct current treatment of metals without the need of a hard working pre-treatment for inducing dislocation, recrystallization, and property variations [30–44]. It is generally believed that the critical current densities for inducing the electric current-induced phenomena exist and are determined by various factors, such as

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Table 1
Experimental conditions of the electric current treatments of metals. AC: alternating current; Ann: annealed; CD x%: cold drawn to x% reduction; CR x%: cold rolled to x% reduction; DC: direct current; EP: electropulsing; HR x%: hot rolled to x% reduction; NA: not available; Th: thickness; ϕ: diameter.

Metal	Geometric shape	Pre-treatment	Electric current treatment		Ref.
			Mode	Condition, A/cm^2	
Al/Cu/Ni/Fe/Nb/W/Ti	Not mentioned	NA	EP	$4–5 \times 10^5$, 60 µs	[2]
Fe/Ti	Wire (ϕ: 0.12–0.51 mm)	Ann 1073 K, 30 min	EP	$0–8 \times 10^5$, < 100 µs	[3]
Ti	Wire (ϕ: 0.12–0.51 mm)	Ann 1073 K, 30 min	EP	$0–1.2 \times 10^6$, 80 µs	[4]
Cu	Wire (ϕ: 0.8 mm)	CR 50%	EP	8×10^4, 90 µs	[5]
Cu	Wire (ϕ: 0.8 mm)	CR 24–76%	EP	8×10^4, 90 µs	[6]
Cu	Wire (ϕ: 0.8 mm)	CD 24%	EP	8×10^4, 90 µs	[7]
Cu	Rod (ϕ: 12 mm)	Extrusion to 12 mm	EP	$5.3–6.2 \times 10^2$	[8]
Cu40.6Zn0.3Pb	Strip (Th: 1 mm)	CR 33%	EP	$1.8–1.9 \times 10^6$, 800 µs	[9]
ZA27 Zn alloy	Wire (ϕ: 1.18 mm)	CD	EP	$2.79–13.36 \times 10^3$, 2300 µs, 100 Hz	[10]
Ni49.2at%Ti	Wire (ϕ: 100 µm)	CD 45 ± 5%	EP	125 W, 1–18 ms	[11]
Ni49.2at%Ti	Strip (Th: 1.32 mm)	CR 40%	EP	$9.5–11.4 \times 10^3$, 80 µs, 150–350 Hz	[12]
Ni49.2at%Ti	Strip (Th: 1.32 mm)	CR 40%	EP	$9.5–11.4 \times 10^3$, 2.5–15 min, 150–350 Hz	[13]
Fe3Si	Strip (Th: 0.3 mm)	CR 23%	EP	70 V, 92–250 Hz	[14]
Fe3Si	Strip (Th: 0.3 mm)	CR 75%	EP	$2.85–3.62 \times 10^4$, 70 µs, 98–173 Hz	[15]
Pearlitic steel	Wire	CD (strain: 1.61)	EP	9.61×10^5, < 150 µs	[16]
22MnB5 boron steel	Strip (Th: 1.5 mm)	CR	EP	8.901×10^4, 60–180 ms, 50 Hz	[17]
IF steel/AZ31 Mg alloy	Strip (Th: 2 mm)	CR 50%	EP	$1.2–2.1 \times 10^3$, 5–960 s for IF steel; $4–8 \times 10^3$, 60–1800 s for AZ31 Mg alloy	[18]
Mg3Al1Zn	Strip (Th: 3 mm)	HR 60%	EP	$2.481–3.508 \times 10^5$, 20–40 µs, 100–150 Hz	[19]
6061 Al alloy	Strip (Th: 0.8 mm)	CR 60%	EP	$2.18–2.24 \times 10^5$, 15 s, 500–800 Hz	[20]
5052-H32 Al alloy	Strip (Th: 2 mm)	CR	EP	$6–12 \times 10^3$, 0.5–1 s	[21]
5052-H32 Al alloy	Strip (Th: 2 mm)	CR 30%	EP	1.1×10^5, 0.5 s, 0.03 Hz	[22]
2024 Al alloy	Strip (Th: 0.5 mm)	CR	EP	$8–16 \times 10^3$, 0.5 s	[23]
2024 Al alloy	Strip (Th: 2 mm)	HR 30%	AC	2×10^6, 0.24 s, 50 Hz	[24]
2024 Al alloy	Strip (Th: 2 mm)	HR 30%	AC	$8.5–25.5 \times 10^3$, 0.1 s, 50 Hz	[25]
7075 Al alloy	Strip (Th: 2 mm)	CR < 30%	AC	2×10^5, 0.22 s, 50 Hz	[26]
7075 Al alloy	Strip (Th: 2 mm)	HR < 30%	AC	2×10^5, 0.22 s, 50 Hz	[27]
3xxx Al alloy	Strip (Th: 1.5 mm)	CR (strain: 1.6,3)	AC	3.3×10^3	[28]
α-Ti	Strip (area: 2 mm^2)	CR 64%	AC/DC	$0–1 \times 10^3$	[29]
Al0.5Cu	Thin line (Th: 500 nm)	NA	AC/DC	3×10^6, 100 Hz for AC; 3×10^6 for DC	[30]
Al	Thin film (Th: 500 nm)	Ann 653 K, 6 h	DC	$1.5–3.0 \times 10^5$	[31]
Cu	Thin film (Th: 300 nm)	Ann 673 K, 1 h	DC	$1–2 \times 10^6$	[32]
Cu36Zn	Strip (Th: 25 µm)	Ann 723 K, 12 h	DC	$4–18 \times 10^3$	[33]
Sn	Strip (Th: 50 µm)	Ann 403 K, 24 h	DC	$5.5–7.5 \times 10^3$	[34]
Sn9Zn	Joint	Ann 373 K, 24 h	DC	2.6×10^3	[35]
Sn9Zn	Strip (Th: 25 µm)	Ann 423 K, 24 h	DC	$2–8 \times 10^3$	[36]
Sn9Zn	Strip (Th: 25 µm)	Ann 423 K, 24 h	DC	$5–10 \times 10^3$	[37]
Sn0.7Cu	Joint	NA	DC	1×10^4	[38]
Sn0.8Cu/Sn1Cu	Strip (Th: 25 µm)/joint	NA	DC	1×10^4 for strip; 2.6×10^3 for joint	[39]
Sn5Bi	Strip (Th: 50 µm)	NA	DC	$4–6 \times 10^3$	[40]
Sn3.5Ag	Strip (Th: 50 µm)	NA	DC	$5–7 \times 10^3$	[41]
Pb5Sn	Joint	Ann 398 K, 24 h	DC	$2.1–5.0 \times 10^4$	[42]
Pb5Sn	Wire (ϕ: 246 µm)/joint	NA	DC	$5–10 \times 10^3$ for wire; 4.2×10^4 for joint	[43]
Pb3Sn/Pb5Sn	Strip (Th: 25 µm)/joint	NA	DC	6×10^3 for strip; 4.2×10^4 for joint	[44]

the effective charge number (Z*) of metals, the pre-treatment methods (annealing, cold rolling, hot rolling…), and the modes of the electric current treatments (electropulsing, alternating current (AC), direct current (DC)). For example, the critical current densities for inducing lattice strain in annealed Cu36Zn and Sn9Zn alloys were reported to be $6.40–7.36 \times 10^3$ A/cm^2 [33] and $2.0–4.0 \times 10^3$ A/cm^2 [36], respectively, under a DC treatment. The present work gives a review on the practices of the electric current treatments and the related microstructure-property variations in metals. The mechanisms of the variations are also presented and discussed.

2. Practices of Electric Current Treatment

The mode of the electric current treatment of metals includes electropulsing, alternating and direct current, as presented in Table 1. The electropulsing and alternating current treatments are generally incorporated with a hard working pre-treatment, such as rolling and drawing. However, the direct current treatment can be applied for inducing microstructure and property variations in metals without the need of a hard working pre-treatment. The experimental conditions of the electric current treatments of metals are summarized in Table 1. The current density applied falls in the range of 10^2–10^6 A/cm^2; the range of the frequency of alternating current is 50–800 Hz; the pulse mode is various as shown in the table.

3. Microstructure-Property Variations and the Physical Metallurgy

Electric current treatment of metals provides thermal energy from Joule heat (thermal effect) and kinetic energy from electron wind force (athermal effect) which together promote the dislocation mobility. The enhancement in the dislocation mobility further results in the acceleration of homogenization, recovery, recrystallization, grain growth, and microstructure and phase transformation processes. The atomic diffusion enhanced by the electric current treatment is generally believed to be a result of the athermal effect of electromigration besides the thermal effect [13,14]. The net diffusion flux (j) driven by the thermal and athermal effects can be described by the following equations [13]:

$$j = j_t + j_a \tag{1}$$

$$j_t = \frac{D}{kT}\tau\Omega \tag{2}$$