Recent advances and challenges in electroplastic manufacturing processing of metals

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Electroplastic manufacturing processing (EPMP) is a relatively new metal-forming process that is energy efficient, environmentally friendly, and versatile. In particular, it can be used to manufacture metals or alloys that are difficult to process by conventional manufacturing protocols. There have been significant advances in EPMP in the past decade, and this review summarizes our current state of understanding and describes recent developments in EPMP. Particular emphasis is placed on describing the mechanisms responsible for the electroplastic effect and microstructure evolution as well as major advances in EPMP of metals. Challenges facing theoretical and experimental investigations are also discussed.

I. INTRODUCTION

When electrical pulses are applied to metals undergoing deformation, the deformation resistance reduces dramatically and plasticity increases significantly at the same time. This influence of the electric current pulses on the plastic flow is called the electroplastic (EP) effect or EPE. In 1963, EPE was first discovered and reported by Troistkii and Likhtman.[1] Subsequently, Troistkii et al.,[2–14] researchers in Russia,[15–32] Conrad et al.,[33–42] and other investigators in the United States[43–46] conducted a series of extensive studies on the effects of drift electrons on the flow stress in a variety of metals. These investigations were carried out by mainly two ways of providing the drift electrons, namely, continuous electrical current and high density (10^3–10^5 A/cm^2) electrical pulses ($\sim$100 μm duration). Besides, these works focused on the study of EP mechanism using three types of mechanical tests, namely uniaxial tension, creep, and stress relaxation.

Traditional manufacturing processes such as drawing, rolling, and punching rely on the use of heat to reduce the forces associated with the fabricated parts. The largest expenditure of time, energy, and labor occurs in the numerous preheating, intermediate heating, and annealing steps. Moreover, the temperatures required by the process are usually quite high, potentially leading to thermal stress, warpage, and reduced tolerance control. Therefore, electroplastic manufacturing processing (EPMP) is one of the most effective ways to simplify the manufacturing processes while enhancing the properties of the final products. Hence, a better understanding and more efficient techniques to exploit the effects of electrical current on microstructure evolution during manufacturing are important to both science and engineering as well as wider applications. This paper aims at summarizing recent major achievements in the field of EPMP of metals and covers both experimental and theoretical works.

II. PIONEERING ELECTROPLASTICITY RESEARCH

In 1963, Troitskii and Likhtman[1] reported that electrical current pulses reduced the stress required to initiate deformation in metals. During electron irradiation of Zn single crystals undergoing plastic deformation, a significant decrease in the flow stress and improvement in ductility were observed when the electron beam was directed along the (0001) slip plane compared with those when it was normal to the plane. The phenomenon was subsequently confirmed by Troitskii[47] and led

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him to conclude that drift electrons could exert a force ("electron wind") on dislocations and such force should occur during the passage of an electrical current through a metal being plastically deformed.

Since then, more work has been carried out on this topic. Troitskii and other Soviet scientists conducted a series of investigations on the influence of direct current pulses on the mechanical properties of metals including the flow stress,[2–7] stress relaxation,[8–11] creep,[12–14] dislocation generation and mobility,[15,16] brittle fracture,[17–19] fatigue,[20] and metal working.[21–32] The observed effect of the electric current pulses on the plastic flow is termed an electroplastic effect (EPE). Stimulated by the Russian work, similar studies pertaining to EPE were carried out in the United States by Conrad and coworkers,[33–39] Varma and Cornwell,[43] as well as Goldman et al.[44] Conrad and coworkers performed experiments to determine the magnitude of the drift electron–dislocation interaction with the application of a current pulse during plastic flow and the physical basis of the interaction. They believed that the electrical current reduced the activation volume and free energy by most likely changing the force–distance curve of the thermal activation process. It was concluded that the observed increase in the pre-exponential term produced by the current pulses arose partly from the increase in the density of mobile dislocations and the area swept out per successful thermal fluctuation as well as the difference between the static and dynamic responses of the test system to the pulsed load drop. The work mostly focused on the effects of the electrical current pulses on the uniaxial tension of metals.

Recently, Andrawes et al. reported that electricity affected the strength and ductility of 6061 T6511 aluminum.[48] They extended the work by examining the changes in the microstructure of the 6061 T6511 tensile specimens after electrical deformation. Ross and Roth also examined in a comprehensive manner the effects of electricity on various materials.[49] This work showed that the electroplastic effect was consistent in most materials regardless of the microstructure, resistivity, or strength. More recently, Zhu et al.[50] studied the effects of dynamic electropulsing on the microstructure and elongation of a Zn–Al alloy. Compared with the non-EP treated alloy, elongation of the EP ZA22 alloy increased by 437% at ambient temperature and a high deformation rate was observed under electropulsing. Accordingly, it appears that electrical current pulses have the potential of lowering the forces required during bulk deformation processes. Furthermore, in addition to reducing the specific energy of the materials, it is hypothesized that concurrent application of electrical current pulses during deformation may increase the materials workability and tool/die lifetime while decreasing the workpiece springback and machine size.

III. ELECTROPLASTIC MANUFACTURING PROCESSING

Traditional manufacturing processes such as drawing, rolling, and punching rely on the use of heat to reduce the forces associated with fabricated parts. Relative to the negative implications associated with hot working, EP manufacturing is an efficient energy-conserving means.[51,52] Russian researchers have already implemented this process in drawing[53–60] and rolling,[61–65] and some of the benefits of metal working are given in Table I. Recently, Tang et al. conducted a series of studies on EP drawing[66–69] and rolling.[70–72] The results confirm the EP effect in metals and point out that EPMP is especially suitable for the manufacturing of metals and their alloys that are otherwise difficult to process using conventional manufacturing processing. For instance, EP punching has been achieved on magnesium alloys by Wang.[73]

A. Electroplastic drawing

In electroplastic drawing (EPD), the current is applied either to the equipment (the drawing dies) or directly to the materials via conventional contacts. In EPD of stainless steel,[54,56–60,74] Cu,[55] and W wires,[58,75] it is found that the current pulses passing through the metal deformation zone reduce the force required for drawing. The reduction in force depends on the current density, pulse frequency, and also pulse direction, clearly illustrating the existence of a polarity effect. Gromov et al.[74] reported that electrostimulation had multiple influences on the substructure formation, showing itself at various structural levels when drawing steel 08G2S and 17GKhAF wires. Recently, Tang and coworkers studied the use of EPE in the cold drawing of different metals.[66–69] Current pulsing during drawing can reduce the deforming resistance of stainless steel 304L.[67] Compared with traditional drawing technology, EPD can reduce the resistivity of the cold-drawn steel wires by more than 10% as shown in Fig. 1. During EPD, formation of the ferromagnetic phase at a low deformation rate is reduced[68] but without electropulsing, a large amount of strain-induced martensite is formed as shown in Fig. 2.

TABLE I. Effects of electric current pulses on metal working (Cu, Fe, stainless steel, Fe-Co, W, Ti, Mg alloys, TiNi alloys).

Reduction in force required for working and in brittleness
Roll W sheet at room temperature
Improvement in surface finish and subsequent mechanical properties of products
Increase in tensile strength and elongation
DRX at low temperature and tilted basal texture formed during rolling Mg alloys
Nanostructure formed during rolling NiTi alloys
Occurrence of phase transformation

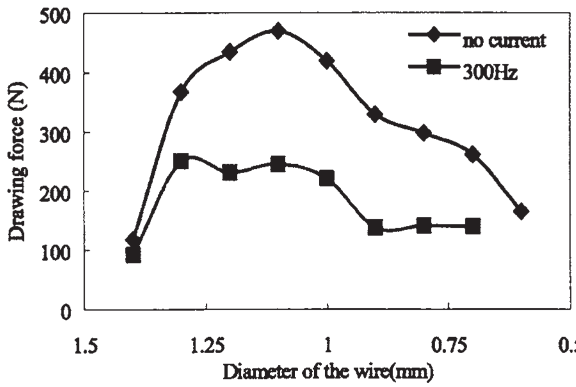

FIG. 1. Drawing force of the wire with 300 Hz current pulses and without current.[67]

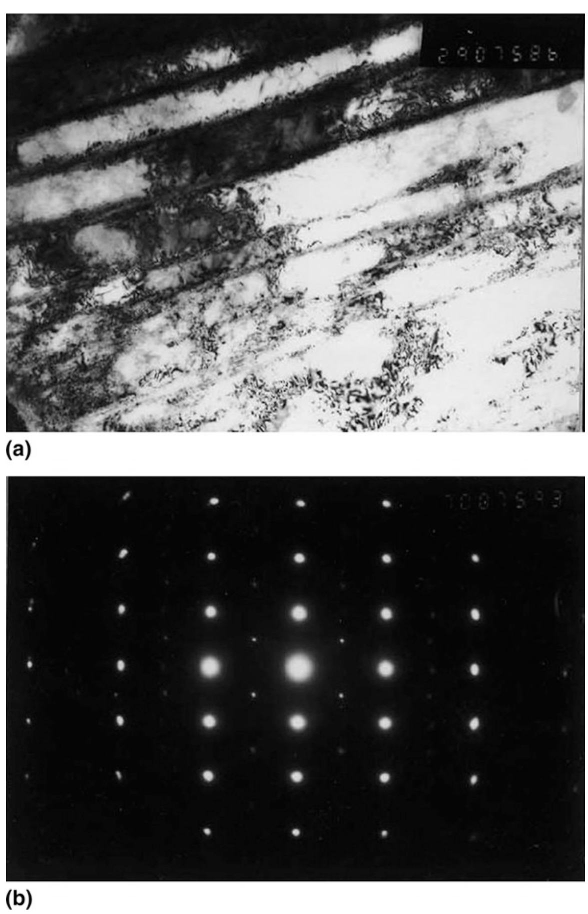

FIG. 2. (a) TEM morphology and (b) diffraction pattern of martensite [211] α in the matrix of austenite [111] γ.[68]

With regard to EPD of magnesium alloy,[69] it is found that the drawing force is reduced to about 25% compared with the conventional wire-drawing process. At a relatively low temperature, dynamic recrystallization (DRX) takes place within a short treatment time, thereby improving the plasticity of the wire. Figure 3 depicts a schematic illustration of the EP drawing system.[69]

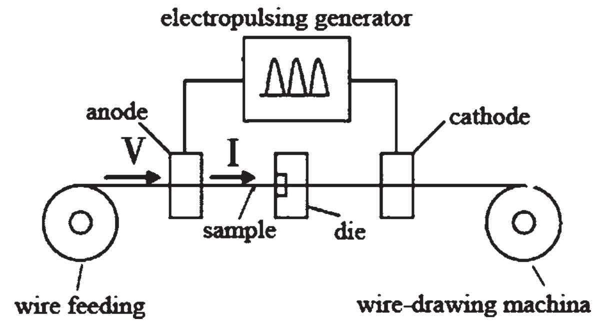

FIG. 3. EP drawing process.

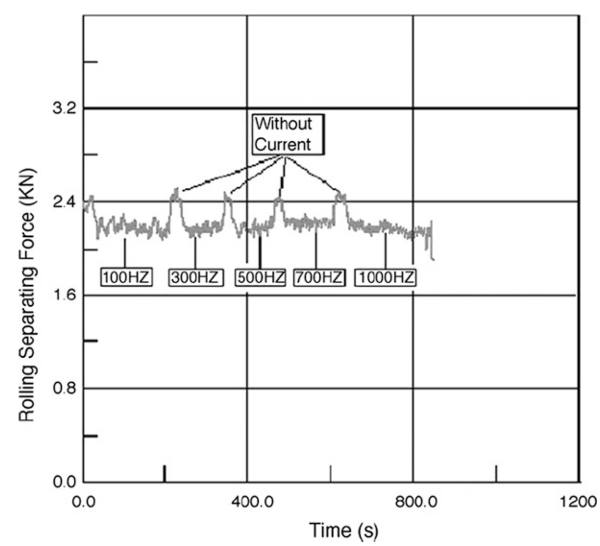

FIG. 4. Diagram illustrating the rolling separation force when varying the electropulsing parameters.[70]

B. Electroplastic rolling

In electroplastic rolling (EPR), the current is applied either to opposite rolls or directly to the materials by means of sliding contacts. Russian researchers have produced tungsten sheets conforming to the highest world standards by EPR.[61–65,76] By passing electric current pulses, Klimov et al.[61] was able to roll W plates into 20 to 30 mm strips at room temperature without a vacuum. Recently, Xu et al.[70,72] obtained magnesium alloy strips using EP rolling at room temperature. During EPR, there is a sharp drop (about 8%) in the rolling separation force as shown in Fig. 4. Moreover, the dynamic recrystallization (DRX) phenomenon takes place at a relatively low temperature in a short time as shown in Fig. 5. More recently, Mal'tsev[65] investigated the properties of metals of technical grade after EPR. The results show that the strength and plastic properties of the metals after undergoing EPR increased as the degree of deformation increased as shown in Fig. 6. Nanostructures have also been formed in TiNi shape memory alloys by EPR.[77–80] Stolyarov et al.[80] reported that EPR of TiNi alloys could

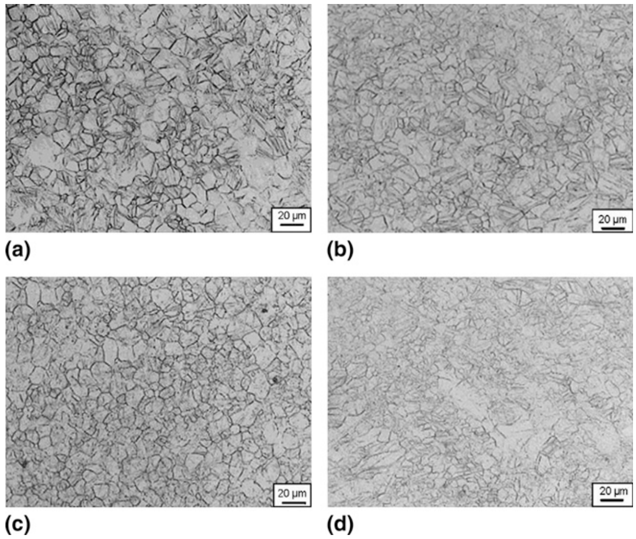

FIG. 5. Microstructures of the AZ31 Mg alloy after ER process using different electropulsing frequencies: (a) 100 Hz, (b) 300 Hz, (c) 500 Hz, and (d) 700 Hz in the middle zone.[70]

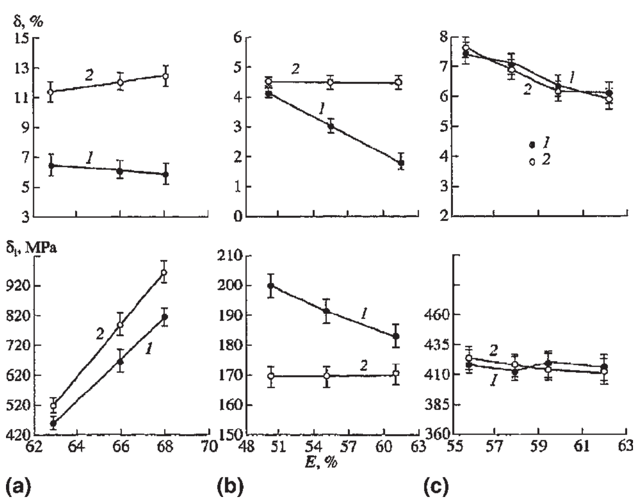

FIG. 6. Effects of the degree of deformation on the elongation δ and relative elongation δ_l in (1) cold-deformed and (2) EPR metals: (a) Ti, (b) Al, and (c) Cu.[65]

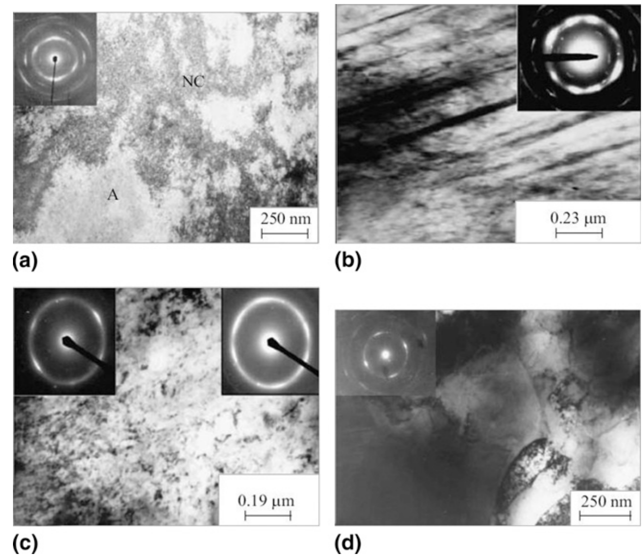

FIG. 7. Microstructure and microdiffraction of the rolled alloy: (a) EPR (j = 80 A/mm^2, e = 0.8; A and NC denote amorphous and nanocrystalline regions respectively); (b) rolling without current electropulsing (e = 0.3); (c) rolling without current (e = 0.8); (d) EPR (e = 1.75. j = 240 A/mm^2).[80]

be used to form different types of microstructures, for example, mixed amorphous-nanocrystalline, nanocrystalline, and ultrafine-grained microstructures. The type of the structure is determined mainly by the density of the pulse current as well as the degree of plastic strain, as shown in Fig. 7. It is found that EPR allows enhanced deformability of TiNi alloys together with improved strength and retained ductility, as shown in Table II. Guan et al.[71] have conducted a study on AZ31 magnesium alloy by conducting large-strain deformation by EPR at room temperature. The results reveal that under the combined thermal and athermal effects, new small DRX grains formed at the grain boundaries and twinned regions consist of ductile bandings. It is interesting to find that the c-axis of the EPR samples is inclined at about 5° to 15° from the normal direction (ND) toward the rolling direction (RD) with slightly weakened basal texture intensity compared with the control sample. Figure 8 presents a schematic illustration of the EPR system.[71]

TABLE II. Room-temperature tension data of NiTi alloy in the CG and UFG states after EPR and annealing at 450 °C.

State	σ_M (MPa)	US (MPa)	YS (MPa)	δ (%)
CG	210	940	600	40
CG + EPR (e = 1.81)	250	1300	1200	9.6
UFG	290	1240	1140	25
UFG + EPR (e = 1.91)	294	1481	1395	8.0

σ_M, martensitic-induced transformation stress; CG, coarse-grained; UFG, ultrafine-grained.

C. Electroplastic punching

In electroplastic punching (EPP), the current is applied either to opposite dies or directly to the materials by means of elastic contact. The effects of electrical pulses on deep drawing of AZ31 magnesium alloy have been studied by Wang.[73] A lower resistance to deformation and better plasticity are achieved when electrical pulses are applied. The drawing of square cups with a depth of 15 mm is obtained by EPP within 2.5 min, and DRX occurs in the big deformed zone at a relatively low temperature of 200 °C as shown in Fig. 9. Figure 10 presents

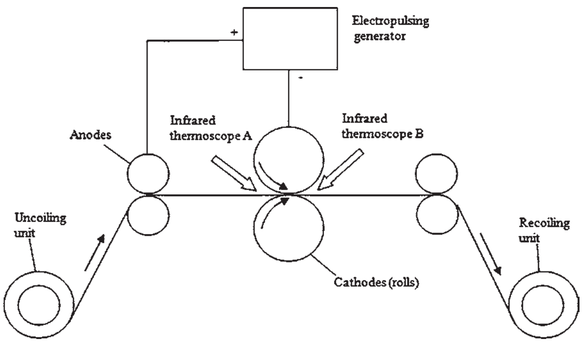

FIG. 8. EP rolling process.

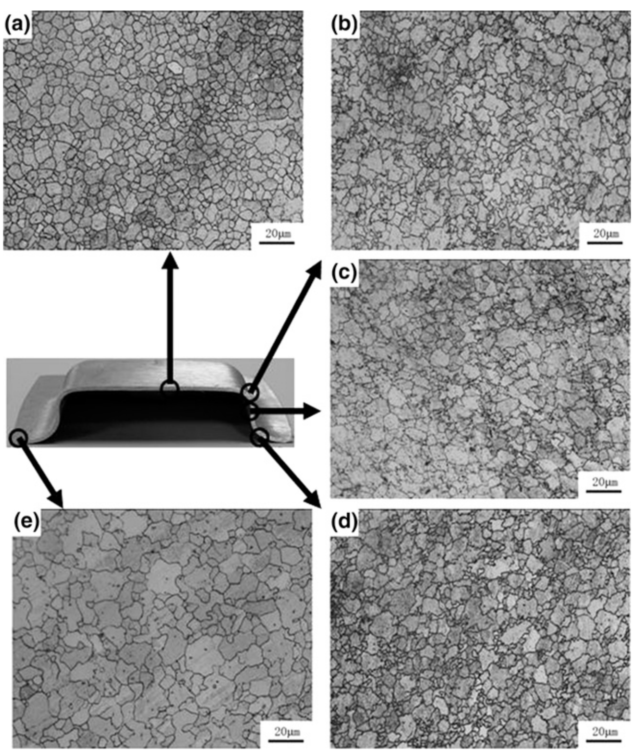

FIG. 9. Microstructure of deformed zones after EPP.[73]

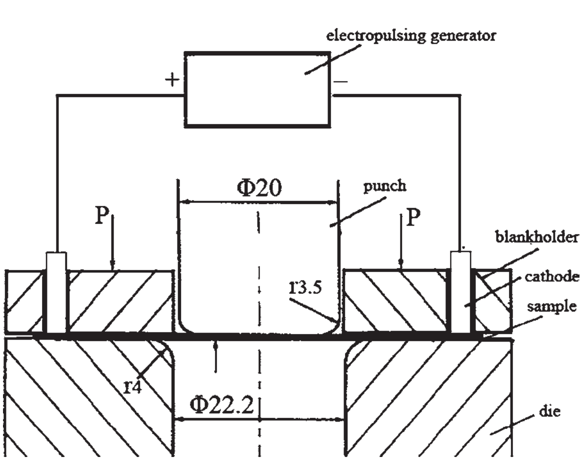

FIG. 10. EP punching process.

FIG. 11. Cups drawn using different electric current parameters: sample 4 with optimal electric current parameters: punch speed = 7.5 mm/min, punch stroke = 12.5 mm; sample 5 with no electropulsing: punch speed = 5 mm/min, punch stroke = 3.5 mm.

a schematic illustration of the EPP system,[73] and the cups drawn with different electrical current parameters are shown in Fig. 11.

IV. MECHANISMS OF THE ELECTROPLASTIC EFFECT

In EP manufacturing including EP drawing, EP rolling, and EP punching, the resistance to plastic deformation decreases significantly. Many reports are generally in agreement that the drift electrons help dislocations to overcome the resistance from obstacles and lattice resistance, thereby resulting in a load drop. The contributions to the load drop from the side effects such as skin, pinch, and heating effects are quite small compared with the total stress changes.

Besides the aforementioned issue of load drop during EP manufacturing, there is another important issue concerning special microstructural changes. The special phenomenon includes DRX and phase transformation at a relatively low temperature occurring in a short processing time, formation of a special texture, and enhanced mechanical properties after EP manufacturing. Some new theories have been postulated to explain these phenomena.

A. Pioneering electroplastic theories

Plastic deformation is defined as the creation and movement of dislocations in materials,[81] and electrical current (also referred to as the electron wind) is defined as the movement of electrons through the lattice of materials. Side effects such as thermal, pinch, and skin effects occur in concert with the direct effect caused by the electrical current. The role of these side effects in EP is an important issue but still controversial. For instance, it has been shown that these side effects cannot totally explain the observed phenomenon,[82–85] and Conrad et al.[36,83] evaluated the contributions of skin, pinch, and heating to EPE.

1. Skin and pinch effects

Localization or concentration of current near a specimen surface (the skin effect) is expected when a high-frequency current is applied. The depth δ is calculated using[36]

$$\delta = \left(\frac{\pi f \mu}{\rho}\right)^{-1/2} \quad , \tag{1}$$

where f is the frequency of the pulses, μ is the permeability, and ρ is the resistivity of the specimen. Exploratory experiments by Conrad and coworkers[36,83] conclude that the current is distributed uniformly throughout the specimen cross section rather than at the surface.

When a high-current pulse is applied, a pinch effect may occur, whereby the pressure created by the intrinsic magnetic field produces radial compressive stress. The pinch effect is estimated by[36]

$$\Delta\sigma_{\text{pinch}} = \nu\mu J^2 a^2/2 \quad , \tag{2}$$

where ν is the Poisson's ratio, a is the specimen radius, and J is the current density. By considering the pinch effect in Ti[36] and Fe[83] specimens, it is concluded that the pinch effect associated with the current pulse is small compared with that associated with the load drops.

2. Heating effect

Joule heating, which is found to be the most important side effect, produces an adiabatic temperature rise[36]

$$\Delta T = \frac{\rho J^2 t_{\text{p}}}{c_{\text{p}} d} \quad , \tag{3}$$

where ρ is the total resistivity, t_{p} is the pulse duration, c_{p} is the specific heat, and d is the density. As shown by Troitskii et al.[82] and Conrad et al.,[36,83] there is good agreement between the measured temperature rise ΔT following a current pulse and that calculated based on Joule heating under adiabatic conditions. The conclusion is that the heating effect is too insignificant to be the cause of EPE. However, some researchers[86,87] believe that the measured EP effect comes entirely from the side effect of Joule heating and that direct effect of electrons is negligible.

3. Electron wind effect

The force resulting from the momentum transfer as the electrons collide with atoms is called the electron wind force.[83] For metal single crystals,[36]

$$F_{\text{ew}} = en_{\text{e}}J\left(\frac{\rho}{N_{\text{D}}}\right) \quad , \tag{4}$$

where F_{ew} is the electron wind force per unit dislocation length, (ρ/N_{D}) is the specific resistivity per unit dislocation length, N_{D} is the dislocation density, and n_{e} is the electron density. Conrad et al.[83–85,88–91] conclude that the enhanced rate of plastic flow is caused by the direct effect of the drift electrons on dislocation motion. Subsequent experiments by Molotskii and Fleurov[92] show that the force is too small to account for EPE. They propose that the magnetic field induced by the current pulses is the major factor for the occurrence of the EPE phenomenon.

B. Recently proposed mechanisms

1. Acceleration of vacancies induced by electropulsing

Xu et al.[70] believe that the combined thermal and athermal effects arising from electropulsing are responsible for the DRX phenomenon in the case of EPR at a low temperature. Acceleration of the activity of vacancies induced by electropulsing gives rise to enhanced dislocation propagation. The dislocation propagation in the case of EPR should be affected by the total flux of vacancies related to the external stress, pushing force of electron wind resulting from electropulsing, and self-diffusing flux of the lattice atoms induced by electropulsing.[88,93] Consequently, the total flux of the diffusing atoms j corresponding to the vacancies activity can be represented as

$$j = \frac{D_1}{kT}\left(\tau\Omega + K_{\text{ew}}\Omega J_{\text{m}} + N_1 \rho e Z_1^* J_{\text{m}}\right) \quad , \tag{5}$$

where D_1 is the lattice diffusion coefficient, k is the Boltzmann constant, T is the absolute temperature of rolling, τ is external stress, Ω is the atom volume, K_{ew} is the coefficient of electron wind force, J_{m} is the amplitude of current density of electropulsing, N_1 is the number of lattice atoms per unit volume, and eZ_1^* is the effective charges of lattice atoms. Accordingly, the thermal effect can be expressed by the rising temperature due to Joule heating, and the athermal effect arises from the periodic drastic impacting force between electrons and atoms (electron wind). It is possible that the athermal effect can partially compensate for the thermal effects for dislocation propagation.

2. Selective effect of electropulsing during EP manufacturing

Research of the microstructural and texture evolution in magnesium alloy AZ31 during large-strain EPR has been conducted by Guan et al.[71] During straining, the crystalline defect distribution is generally heterogeneous and the electrical resistivity is sensitive to the microstructural details of the materials such as grain boundaries, dislocations, vacancies, twins, and so on. When electropulsing is conducted through a metal specimen being deformation, thermal and athermal[94,95] effects are stronger because of the big regional resistivity and the strong detour of the current in the area with defects. This is termed the "selective effect" of electropulsing.

During EPR, the thermal and athermal effects give rise to an additional driving force:

$$\Delta P = P_{\text{th}} + P_{\text{ath}} \quad , \tag{6}$$

where P_{th} is the local thermal compressive stress given by $P_{\text{th}} = (2a\Delta S \text{grad}T)/\varphi$ [ΔS] is the difference in the entropy between the grain boundary and crystal (approximately equal to entropy of melting), grad$T$ is the temperature gradient, $2a$ is the thickness of the grain boundary, φ is the atomic volume, P_{ath} is the electron wind force given by $P_{\text{ath}} = (\rho_D/N_D)en_e j$, ρ_D/N_D is the specific resistivity per unit dislocation length, N_D is the dislocation density, n_e is the electron density, and j is the current density. In EPT, the total driving force is:

$$P_{\text{EP}} = P + \Delta P = P_V + P_R + P_{\text{th}} + P_{\text{ath}} \quad , \qquad (7)$$

where P_V is the volume energy and P_R is the grain-boundary energy. The velocity of the moving boundary during EPR is given by

$$v_{\text{EP}} = MP_{\text{EP}} \quad , \qquad (8)$$

where M, the boundary mobility, is usually assumed to vary with temperature according to $M = M_0 \exp[-Q/RT]$, M_0 is a constant, T is the absolute temperature, Q is the activation energy for boundary migration, and R is the gas constant. Hence, the effects of the rolling reduction corresponding to the driving pressure P and current density corresponding to ΔP on the velocity of the moving boundary are significant.

The results indicate that as J_m and J_e become larger, substantial athermal and thermal effects are produced as P_{ath} and P_{th} increase sharply. Consequently, higher stored energy and faster boundary migration ensue enabling XRD occurrence at a relatively low temperature.

3. Electropulsing-induced phase transformations

In recent years, many studies[96–100] have focused on the effects of electropulsing treatment (EPT) on the solid-state phase transformation in metals. Conrad[85] reported that an electric current could have a significant effect on phase transformation. The extent and direction of the effects depend on the composition and prior treatment of the materials and the density and frequency of the current. Zhu et al.[101,102] investigated the microstructural changes and phase transformation in an EPT ZA22 alloy wire. The results show that electropulsing tremendously accelerates phase transformations in two stages: (i) transformations from supersaturated state approaching the final stable state in a way of quenching and (ii) reverse transformations from the final stable state to a higher temperature state in a way of upquenching. The phase transformations in the quenching stage are faster than the reverse phase transformations in the upquenching stage by 5 times and at least by 6000 times compared with that in the aging, i.e., the non-EPT processes.

The driving force for phase decomposition consists of various parts: chemical Gibbs free energy, surface energy, strain energy, the electropulsing-induced Gibbs free energy, and so on:

$$\Delta G = \Delta G_{\text{chem}} + \Delta G_{\text{stress}} + \Delta G_{\text{surf}} + \Delta G_{\text{EP}} + \dots \quad . \qquad (9)$$

The chemical Gibbs free energy, ΔG_{chem}, is considered a main driving force as far as thermodynamics is concerned. The strain energy, ΔG_{stress}, includes various internal strain energies that may be available, for instance, thermal stress during solidification of the melt and external strain energy because of drawing, rolling, punching, and so forth. With the addition of electropulsing-induced Gibbs free energy, ΔG_{EP}, the total Gibbs free energy is increased thereby significantly increasing the driving force in the phase transformation. The driving for the phase transformation in the quenching stage consists mainly of $\Delta G_{\text{EP}} + \Delta G_{\text{stress}} + \Delta G_{\text{chem}}$, while that for the reverse phase transformations in the upquenching stage is $\Delta G_{\text{EP}} + \Delta G_{\text{stress}} - \Delta G_{\text{chem}}$.[101,102] The $\Delta G_{\text{EP}} + \Delta G_{\text{stress}}$ becomes the driving force against, ΔG_{chem}, the antidriving force for the reverse phase transformations in the upquenching stage.

Jiang et al.[103,104] reported that EPT significantly accelerated the spheroidizing and dissolution processes of the β phase in an aged Mg–9Al–1Zn (AZ91) alloy strip because of reduction in the nucleation thermodynamic barrier and coupling of the thermal and athermal effects of EPT. They[105] found out that temperature played a crucial role in the effects of EPT on the dissolution kinetics of the β phase in the AZ91 alloy. The contribution of athermal effects of EPT to the dissolution kinetics of the β phase increases sharply with temperature and becomes dominant when the temperature is higher than a critical value. An adequate thermal effect resulting from the Joule heating effect of EPT should be necessary for effective operation of athermal effects resulting from the interaction between electrons and atoms.

In spite of recent progress, our current understanding of the mechanism pertaining to EP effect on the phase transformations is still inadequate. Furthermore, our understanding of the detailed atomic mechanisms associated with the effects of the current on phase transformation during EPMP is still rudimentary. More systematic studies involving careful, definitive, and high-resolution microscopy are required to fathom the nucleation and growth of the transformation products.

V. CHALLENGES

Several challenges are still ahead before successful realization of the roadmap concerning commercial applications of EPMP. Some of the key issues are listed below:

(i) *Development of EP mechanism.* During EP manufacturing, the combined thermal and athermal effects arising from electropulsing facilitate metal forming. It is important to quantify the values of thermal and athermal effects to clarify the real reason for the EP effect and provide a theoretical basis for using electrical energy more efficiently.

(ii) *Refinement of current and exploitation of new EPMP*. Commercialization of EPMP requires more stable and reliable processes. More experimental and theoretical studies must be performed in this direction. Moreover, new discoveries pertaining to EPMP, for example, electroplastic turning and severe electroplastic deformation, are imperative to the continuous sustainability of the technology.

(iii) *Interdisciplinary effort*. Widespread applications of EPMP depend on active participation from scientists and engineers in different disciplines. To understand this useful but not well understood technology, development of a cross-functional scientific workforce that transcends the conventional limits of various disciplines is required.

Although the prospects of EPMP are excellent, one of the most serious problems arise when the pieces being formed (e.g., by rolling, punching, and so on) are thin but relatively wide. In this case, how to pass large electropulses to the deformation zone is problematic. More robust power sources are needed to increase the process efficiency but inevitably add to the manufacturing costs.

VI. CONCLUDING REMARKS

EPMP has great potential as a commercial technique. It has the merits of reduced deformation resistance, improved plasticity, simplified processes, increased energy efficiency, lower cost, and better products. The fabrication technology employing electrical pulses can strongly affect the morphology and metal properties, but better theoretical understanding of the EP mechanism and EPMP is crucial. Although substantial progress has been made in the past few years, further progress is needed to realize the full potential of this technology.

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