

Influence of Pulse Current on Plastic Processing of Materials

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Abstract

Pulse current is applied when the metal material is plastically deformed, in terms of mechanical properties: the flow stress of the material decreases and the plastic deformation ability increases; in terms of microscopic effects: the introduction of current can improve the state of the structure, accelerate the recrystallization process, and refine the grains. The application of current in plastic processing such as electro-plastic drawing, hot stamping technology and superplastic forming technology is illustrated. The application of pulsed current in the field of plastic processing can strongly promote the development of cutting-edge manufacturing, especially in the aerospace manufacturing industry. A large number of studies have also proved that pulse current has far-reaching research significance and wide application value in the field of material processing.

Keywords

Electro-plastic effect, current, drift electron, plastic processing, grain refinement.

1. Introduction

Electro-plastic processing is the process of introducing current into the material processing process, using the effect of current on the material to improve the performance of the material. According to the different stages of current action, the technology can be divided into two categories: one is to introduce current before the material is formed, power off when forming materials, and the material is heated by the thermal effect of current. The self-assembly heating stamping is a typical application. The other application is to apply current during the molding process of the material, and the electro-plastic effect is used to improve the plastic deformation ability of the material and reduce the flow stress. In 1963, former Soviet scientists O.A.Troitskii and V.I.Lichtman[1] first discovered the forces that interact with drifting electrons in metal crystals and dislocations. When they were subjected to electron beam irradiation tensile test on single crystal zinc, it was found that when the irradiation direction was parallel to the sliding direction of zinc to $\langle 1120 \rangle$ and the slip surface $\{0001\}$, the dislocation ability of zinc was significantly enhanced, and the deformation resistance was decreased, and the elongation increased. When the electron beam is irradiated perpendicularly to the direction of the slip system, brittle fracture occurs. After this, the former Soviet Union and American scientists[2-4] have done a lot of research in this area. But so far, the large-scale engineering application of electro-plastic processing is still very limited. Therefore, with the deepening of electro-plastic research, the electro-plastic effect will be applied in more processing techniques, while improving production efficiency. It also improves the production process and improves the quality of the products, making the application of traditional materials processing methods more extensive.

2. Macroscopic effect of current in plastic processing of materials

After introducing current into the plastic processing process, scholars have successively discovered a variety of phenomena that have not appeared in the traditional processing. So far, it is generally believed that the electro-plastic effect is a composite effect composed of four physical effects: Joule heating effect, magnetic field compression effect, skin effect and pure electro-plastic effect.

2.1 Joule heating effect

The section Joule heating effect Temperature can reduce the deformation resistance of the material. When a current is applied to the deformed sample, the Joule heat generated by the resistance of the material raises the temperature, which can be expressed as[5]:

$$Q = I^2 R t \quad (1)$$

Where: Q is heat; I is current; R is resistance; t is time. The specific theoretical temperature rise is[3]:

$$\Delta T = \frac{\rho J^2 t_p}{C_p d} \quad (2)$$

Where: ρ is the resistivity; J is the current density; t_p is the pulse duration; C_p is the constant pressure heat capacity; d is the density. On the basis of summarizing the predecessors, Sprecher et al. obtained a more realistic temperature rise calculation formula[6]:

$$\Delta T = \frac{\int_0^t \rho I^2(t) dt}{C_p A^2 d} \quad (3)$$

Where: $I(t)$ is the instantaneous current value; A is the material cross section.

Okazaki et al. studied the effect of current on the interaction between different crystal structures and electrons and dislocations. It was calculated that when the material was stretched under current, about 60% of the stress drop depends on Joule heat. Zhou et al.[7] found that the Joule heat had the greatest effect on dislocation promotion when the effective current density was $9.03 \text{ A} \times \text{mm}^{-2}$. Zou Lei et al.[8] pointed out that Joule heat makes the fish bone eutectic carbide at the grain boundary of as-cast W6Mo5Cr4V2 high speed steel disappear, which is beneficial to material deformation.

2.2 Magnetic field compression effect

When the material is energized, a magnetic field is generated around the material, which in turn acts on the material to cause stress. However, due to the high-frequency pulse current, the magnetic field compression effect produces less stress and has little effect on plastic deformation.

2.3 Skin effect

When a high-energy pulse current passes through the material, the current will flow toward the surface of the material. This phenomenon is called the skin effect. It results in an uneven temperature distribution across the cross-sectional area of the material, which causes an increase in thermal stress and a decrease in tensile stress[9]. Okazaki et al.[2-4] believe that the increase in heat and the increase in plasticity caused by the effects of skin effect and magnetic field compression effect are small and negligible.

2.4 Pure electro-plastic effect

In 1963, O.A.Troitskii[10] reported for the first time that electrons in metals can help dislocations overcome obstacles that hinder motion, that is, drift electrons have a thrust or electron wind (Electron wind force) acting on dislocations, making dislocations add and slip, improving the plasticity of the material, which is the concept of electro-plastic effect. Soviet scholars think that the main features of the electro-plastic effect are: a). Reduce the force required for metal pressure processing; b). Reduce the brittleness of the material; c). Increase the surface finish of the material; d). Improve the mechanical properties of the material, and increase the tensile and elongation of the material. e). The

texture of the material has changed; f). The microstructure has changed. However, the current theory and mechanism of electro-plastic effect are not very clear. People have their own assumptions or theories, which are summarized as follows:

- a). The drifting electrons in the metal form an electronic wind under the action of an electric field, and the force generated by the electronic wind against dislocations acts like an external force acting on the dislocation;
- b). Drift electrons may affect Gibbs free energy, producing a difference ΔG , which hinders the decline of intensity, but there is still no specific experimental data, which needs further research and discussion;
- c). Drift electrons may have an effect on stacking fault energy and activation volume, which includes dislocation length and dislocation width, and the dislocation width is affected by stacking fault energy;
- d). Drift electrons increase the dislocation density and change the distribution and structure of dislocations.

The electronic wind theory has now been accepted by a large number of researchers, and the electronic wind model has also been extensively studied and utilized. Li et al.[11] analyzed the kinetics of electro-plastic dislocation activation of Zn-22%Al alloy, which showed that the electronic wind enhanced the internal dislocation ability of the crystal, which made the grain boundary slip easy to carry out and the climbing was carried out. Liu et al.[12] studied the electric pulse to promote the forming ability of SiC/Al alloy materials, and found that in the case of drifting electron impact dislocations, an electronic wind force is generated, causing dislocations to proceed along the direction of the current, thereby promoting deformation.

3. Microscopic effect of current in plastic processing of materials

In the plastic processing process, the influence of current on the material is not only reflected in the macroscopic effect, but also in the material evolution of the material. In 1990, Conrad et al.[13] found that the electrical pulse treatment during the recrystallization of copper reduced the annealing temperature, recrystallization time and recrystallized grain size. Du et al.[14] found that the AZ31 alloy with equal channel angular pressing and electric pulse treatment compared with the AZ31 alloy treated only by equal channel angular pressing, the recrystallized grain size of the treated process increased slightly, the failure rate of stretching is significantly improved and the tissue is more uniform. Jin et al.[15] used electric pulse technology to treat the rolled ZK60 magnesium alloy steel plate. Compared with thermal aging, both undergo static recrystallization. The difference is that the electric pulse treatment is more likely to produce static recrystallization behavior. And more fine recrystallized grains can be obtained, as shown in Figure 1. However, the temperature of the surface of the two methods after treatment is similar, and Jin et al. believe that the extra energy induced by electric pulse G_e enhances the driving force of recrystallization, leading to the occurrence of static recrystallization, and it is deduced that it is sufficiently high. The current density and low duty cycle allow for finer recrystallized grains.

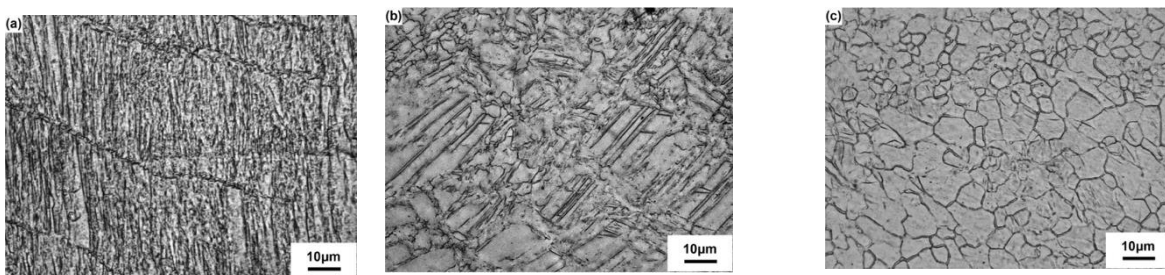


Figure 1. Microstructure of different samples for comparison experiments: (a) as-rolled, (b) after heat treatment at 449 K for 10 min and (c) after 30 μ s-100 Hz EPT for 10 min.

4. Application of current in plastic processing of materials

Today, with rapid economic development and increasingly tight resource constraints, the efficiency and cost of precision forming of advanced materials, especially lightweight alloys, in the aerospace manufacturing industry has always been an important factor affecting the development of new materials and design process solutions. Since the current can generate Joule heat and electro-plasticity through the metal material, the heating efficiency and the forming efficiency can be improved, and applications are applied in the fields of hot stamping, rolling, punching, and drawing.

4.1 Electro-plastic drawing

Electro-plastic drawing is a processing technique that applies the electro-plastic effect to the metal drawing process. Schematic diagram of electro-plastic drawing device is shown in Figure 2. The electro-plastic effect of high-density pulse current is used to promote the deformation during the plastic deformation of the wire, reduce the drawing force, improve the forming limit of the wire, and improve the microstructure and comprehensive mechanical properties of the wire. Li et al.[16] studied the influence of current parameters on the electro-plastic drawing process, indicating that the higher the current intensity, the better the electro-plasticity of the material. With the development of simulation technology, researchers began to use simulation technology to simulate the experimental study of electro-plastic drawing process. Xie et al.[17] used the Johnson-cook model to carry out the finite element simulation experiment on the thermoelectric coupling structure of AZ31B magnesium alloy sheet. The results show that the electric pulse can improve the recrystallization rate and reduce the flow stress, which is beneficial to the drawing experiment.

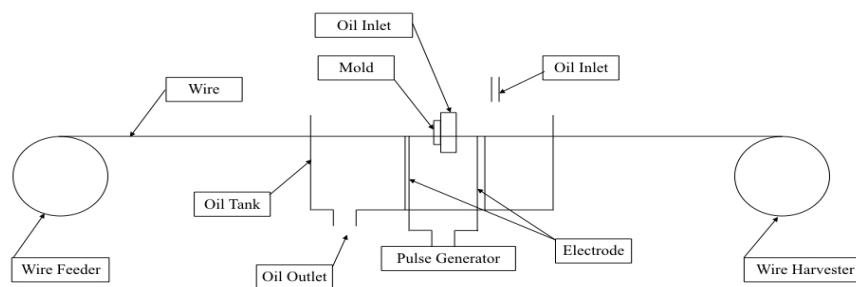


Figure 2. Schematic diagram of electro-plastic drawing device

4.2 Hot stamping technology

Current-assisted forming, that is, current is still present during the forming process, exhibiting significant advantages. Wu[18] processed the elongated structural parts by current-assisted forming, as shown in Figure 3. The material is DP1180 high strength steel. The results show that the surface quality of the structural parts produced by this method is good without scratches, no obvious cracks appear, the surface quality after pickling is very good, the thickness is uniform everywhere after forming, no obvious thinning, and the forming quality meets the actual engineering requirements.



Figure 3. High-strength steel slender structure parts

4.3 Superplastic forming technology

Superplastic forming is a process method in which a superplastic metal is used as a mold cavity blank, and a process punch is pressed into the blank to realize a mold cavity forming process in a superplastic state. Zhao[19] used a process of current-assisted superplastic forming in the process of trial production of Ti31 bellows. Different stages of bulging pressure are different, and the air pressure is increased in turn, and the bulging is completed in three times. Figure 4 is the formed part, the surface of the bellows after pickling is bright, without obvious scratches and pits. The current assisted expansion is highly efficient and the entire forming process can be controlled within 6 minutes.



Figure 4. Titanium alloy bellow

5. Conclusion

- A. The electro-plastic effect is a composite effect composed of four physical effects: Joule heating effect, magnetic field compression effect, skin effect and pure electro-plastic effect. When drifting electron impact dislocations, electronic wind is generated, and dislocations are made along the current direction, thereby promoting plastic deformation of the material;
- B. The current affects the microstructure of the material, and the current enhances the driving force for recrystallization, resulting in the occurrence of static recrystallization.
- C. Compared with the conventional drawing process, the electro-plastic drawing technology reduces the deformation resistance of the material, improves the plasticity, improves the surface quality of the product, increases the forming limit of the material, and achieves continuous wire drawing without any intermediate annealing, thereby improving the productivity.
- D. The mechanism of electro-plastic effect remains to be further studied. There are some differences in the effects of current or electric field on materials of different materials and different processing techniques.

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