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ELECTROPLASTIC EFFECT IN MAGNESIUM ALLOY AZ31 USING SUPERCAPACITORS

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In this work, a pulsed electric current is applied to a specimen simultaneously with a quasi-static uniaxial tensile load. To do so a short-time current pulse generator, inducing supercapacitors was designed and manufactured. The experiments with low operating voltage were performed at different electric current pulse period and frequency. The electroplasticity of AZ31 magnesium alloy under a pulsed electric current is investigated experimentally. Appropriate control of current parameters makes it possible to change not only the stress levels in the process, but also achieved plastic strain values. The result of the present study with low operating voltage is expected to provide a basis to develop advanced metal forming processes using electroplasticity.

Keywords: magnesium alloy, electroplastic effect, stress-strain curves, tensile test, metallographic research

INTRODUCTION

The automotive industry is continuously seeking more effective ways of forming modern materials used in sheet pressing processes. Magnesium alloys are an example of new materials, while electromagnetic forming and electrically assisted forming are examples of advanced methods. The electrically assisted forming method takes advantage of the so-called electroplastic effect. This effect occurs in metals when they undergo plastic deformation while simultaneously subjected to pulsating high-density current flow. The consequence of the electroplastic effect is a broad change of the deformed material's properties, and this particularly pertains to plasticizing stress, internal stresses, material defects, and evolution of the microstructure.

Research on the electroplastic effect was preceded by studies on the effect of a magnetic field on plastic deformation, conducted by Kravchenko [1] in 1970. He demonstrated that a strong magnetic field has an influence on the behavior of dislocations and reduces a material's plastic properties This change of metals' plastic properties under the influence of an active magnetic field was called the magnetoelastic effect. In turn, Troistkii [2] and Conrad [3-6] discovered that materials' properties change under the influence of pulsating high-density current flow during plastic deformation, and they called it the electroplastic effect. This effect can successfully be applied to specific plastic forming operations [7].

The rolling process was an example of a practical application of the pulsating current flow technique in plastic working of metals [8]. AZ31 magnesium alloy, in the form of a specimen with a width of 2 mm and thickness of 0,89 mm, was applied as the tested material. A reduction of the rolling force acting on the specimen was observed during electro-pulse deformation. Resistance to cracking was also increased. Another application of the electroplastic effect is to change the structural phases of a material, with the effect of increasing fatigue strength [9]. The observed evolution of microstructure may lead to the formation of nanostructures in conventional materials even after a single impulse [10].

The microscopic electroplastic effect mechanism has not yet been explained precisely. There are three main models attempting to explain this mechanism: the model of Troitskii et al. [11], stating that the motion of electrons caused displacement of dislocations during plastic deformation, the model of Conrad [12] et al., suggesting that thermal interactions are the main factor in changing plastic strain, as well as Molotskii's model [13], stating that displacement of dislocations is caused by the action of the magnetic field induced by flowing current.

Recent studies concerning electro-pulse deformation [14-15] suggest that it is a combination of two factors: released Joule heat and the electroplastic effect. Ultimately, despite much progress of work in this direction, this matter is still controversial and requires further research.

The objective of this work was to create a testing station that would apply the electroplastic effect by means of supercapacitors and use it to apply plastic strain to AZ31 magnesium alloy. The most important advantage of this station is that it uses a low operating voltage (up to 3 V) and utilizes the advantages provided by supercapacitors. This paper presents tests concerning the electroplastic effect that occurs during a uniaxial tensile test. The existence of the electroplastic effect was demonstrated, meaning that the material's properties changed under the influence of pulsating high-density current flow dur-

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ing deformation. The material’s hardening curve can thus be changed be selecting the proper current flow parameters. The novelty presented in this paper is the first application of supercapacitors in tests of this type for the purpose of generating current impulses. Low voltage and the advantages provided by supercapacitors create the possibility of broader application of the electroplastic effect in industrial plastic forming processes.

HIGH-CURRENT IMPULSE GENERATOR

A current impulse generator utilizing supercapacitors, also known as ultra-capacitors or double-layer capacitors, was used to induce the electroplastic effect during tests. Capacitors of this type operate on the principle of taking advantage of a double Helmholtz layer, which is the area on the boundary of two phases distinguished by statistically non-uniform distribution of electrons or ions in both phases (electrons gathered in the capacitor’s electrode and ions from the solution accumulated on its surface). In a state without charging, ions are arranged as seen in Figure 1b, and they are distributed chaotically throughout the entire electrolyte, which is divided by a separator.

If voltage is applied to the appropriate terminals of the supercapacitor (lower than boundary voltage values), ions found in the electrolyte begin to move in the direction of the appropriate electrodes – anions in the direction of the anode and cations in the direction of the cathode (Figure 1a). However, current does not flow and ions do not penetrate to electrodes. They only gather near them, forming the double layer. This is also where carriers of charge are concentrated, with the same value as the charge accumulated on the electrode’s surface but with the opposite sign. To obtain higher capacities (approx. 10 000 times greater than those of conventional capacitors), a very large contact surface of the carbon electrode material (nanotubes) with the electrolyte is applied. The biggest advantages of supercapacitors are: high impulse power, high energy density, lifetime, high efficiency (from 84 % to 95 %), low weight and low harmfulness to the environment. The number of work cycles, which can exceed one million, is an important functional advantage of supercapacitors.

A high-current impulse generator was designed and built with the application of supercapacitors, and its diagram is shown in Figure 2. The most important parameters of the generator are: maximum working voltage 2,7 V, capacity of capacitor bank 14 000 F (4 x 3 500 F), impedance of single capacitor < 200 μΩ, impulse current up to 15 kA. Electronic capacitor switching was applied using MOSFET transistors. The impulse generation system for transistor control makes it possible to use any shape of current impulse progressions over time.

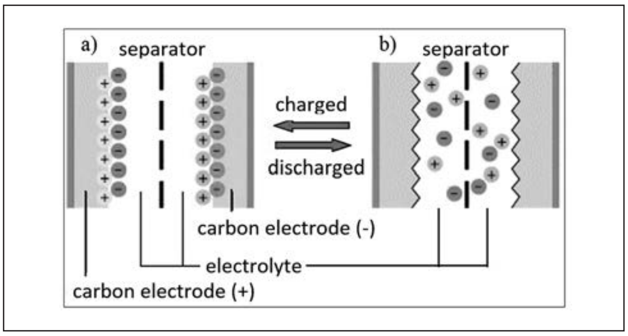

Figure 1 Principle of supercapacitor operation.

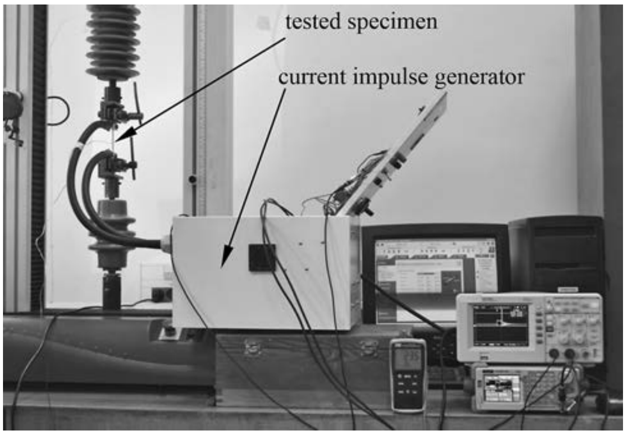

Figure 2 Electroplastic effect testing station. The specimen was completely insulated from the strength tester in this station by means of hybrid insulators.

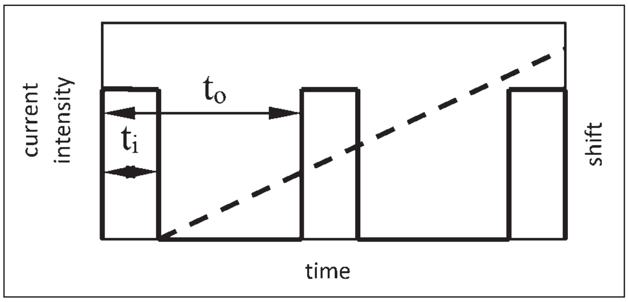

Figure 3 Pulsating current parameters.

TESTING STATION

A special testing station was made to perform electropulse deformation processes, and it consisted of a properly adapted Instron 3369 strength tester, a high-current impulse generator, a specimen temperature measurement system, and measurement instrumentation [16]. A general view of the station is shown in Figure 2.

EXPERIMENTAL TESTS

To conduct tests of the electroplastic effect, the uniaxial tensile test was applied with simultaneous pulsating flow of electrical current. Current was supplied to the specimen by means of copper wires and screw terminals. The specimens used had a width of 11 mm and a measuring based with a length of 100 mm. The speed of the strength tester’s beam amounted to 1 mm/s. Specimen temperature was measured over the course of the tension process by means of a thermocouple. Positive, rectangular current impulses with the following param-

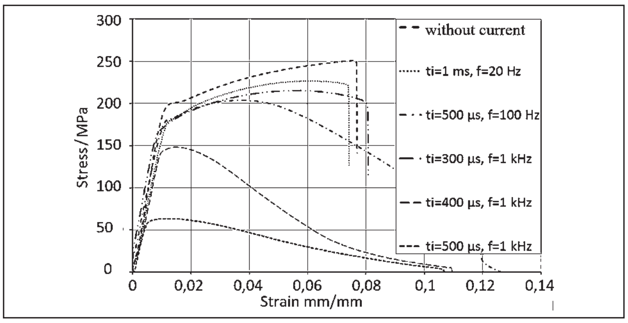

Figure 4 Stress-strain curves of AZ31 magnesium alloy for different current parameters.

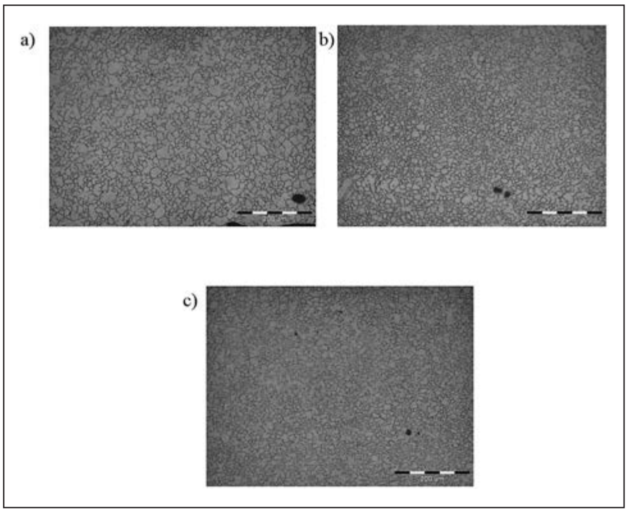

Figure 5 Metallographic photographs of selected specimens.

eters were applied: impulse duration t_i, period duration to and frequency (Figure 3).

Sheet specimens in as-delivered conditions, made from AZ31 magnesium alloy with a thickness of 1,01 mm, were used in tests, and specimens were cut perpendicularly to the rolling direction.

RESULTS

The results obtained from tensile testing of AZ31 magnesium alloy are shown in Fig. 4. Stress-strain curves change their position, are found below the curves obtained without the application of current, and are dependent on its parameters. The largest electroplastic effect is visible for the specimen with a current impulse duration of 500 µs at a frequency of 1,0 kHz. Two fold behavior of the material was observed, depending on activation of specific slip systems. The first three specimens behaved in a manner typical of cold deformation under the influence of current, and the behavior of the last three was typical of hot deformation (although the maximum temperature at the end of the test amounted to 123°C). Temperature reached by the samples during the tensile test was recorded by a thermovision camera FLIR T440.

Figure 5 presents metallographic photographs of the tested specimens, respectively: a) specimen without current, b) second specimen with current, c) final specimen.

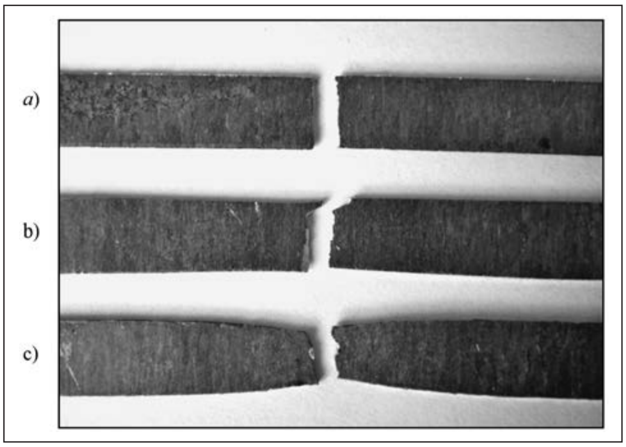

Figure 6 Appearance of specimens subjected to tensile stress after breaking.

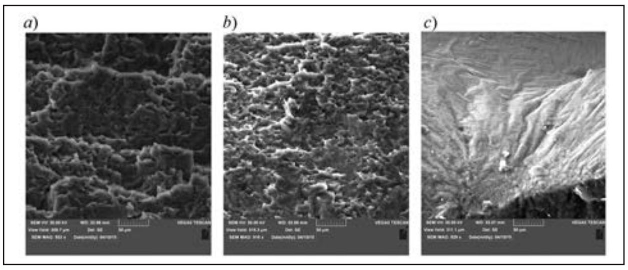

Figure 7 SEM: appearance of fracture site of specimens subjected to tensile stress after breaking.

Dynamic recrystallization (DRX) was not observed to occur in specimens with current, so it could not have been the cause of dynamic weakening of the material. The cause of dynamic weakening of material in specimens with current flow could therefore have been grain rotation to an orientation facilitating deformation of the material.

Varying specimen behavior also manifested in different cracking mechanisms, as shown in Figure 6: a) specimen without current, b) for first two specimens with current, c) for last three specimens.

Figure 7 presents the appearance of a crack surface viewed under Scanning electron microscope (SEM) for previously analyzed specimens. In the case of specimens with current flow, local melting of the material occurs, and the last specimen is distinguished by a nearly smooth fracture surface.

CONCLUSIONS

The application of the novel impulse generation utilizing supercapacitors creates real capabilities of using the electroplastic method to form materials on an industrial scale while preserving the required work safety (voltage up to 3V). The developed current generator, with small overall dimensions, allows for realization of the high-frequency electroplastic effect, which was not made possible by earlier solutions. Appropriate control of current parameters makes it possible to change not only the stress levels in the process, but also achieved plastic strain values. The ability to apply the presented EPE method instead of hot working is another advantage.

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Note: The professional translator for English language is RAZUT, Białystok, Poland