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Electrically-assisted forming of 5754 aluminium alloy under different strain conditions

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Abstract. Electricity-assisted forming processes can significantly improve material ductility and process efficiency. However, further research into different strain conditions is necessary, for example, in stamping processes. In this study, tensile and deep drawing tests of the 5754 aluminium alloy were carried out with the application of current pulses on a specially constructed experimental setup. The study showed that it is possible to increase the plasticity of the material. The main cause responsible for the increase in plasticity was dynamic recovery.

Introduction

The use of light metal alloys with high specific strength helps reduce the weight of vehicles and thus reduce exhaust emissions in the automotive industry [1]. The formability of aluminium and magnesium alloys is generally low at room temperature [2]. Warm and hot forming processes improve formability; however, this results in higher energy consumption and generates problems such as dimensional accuracy and lubrication effectiveness reduction [3].

The formability of aluminium alloys (AA) can also be increased by applying current pulses during its deformation. This method is called Electrically-Assisted Forming (EAF) and has many advantages over conventional forming methods, such as reducing flow stress and increasing material formability [4]. Previous studies have shown that thanks to the additional application of current pulses, it is possible to increase the elongation of the 5052-H32 aluminium alloy [5] and the AZ91 magnesium alloy [6] even more than three times. This large increase in elongation can be explained by the localized Joule heat theory [7]. Nevertheless, other studies have shown that low-temperature pulsed current-assisted deformation can also lead to a significant improvement in the plasticity of zinc [8] and titanium alloys [9]. These changes can be explained by some athermal phenomena (electroplastic effect) [10] or reconfiguration of crystal lattice defects [9]. Further research is needed to precisely determine the impact of thermal and athermal effects.

Although the physical basis of the phenomena occurring during EAF processes is still not clearly defined, many attempts have been made to implement electrically-assisted (EA) industrial processes. Zimniak et al. [11] showed that it is possible to reduce the drawing force in the cooper EA wire drawing process. The products obtained in this way are characterized by better ductility, with no decrease in strength. Similar results were obtained in the rolling process of the AZ31 magnesium alloy [12] supported by the application of current pulses. Xie et al. [13] demonstrated that it is possible to increase the plasticity of the AZ31B magnesium alloy sheet in the EA deep drawing process. However, in the case of other alloys [14], [15] the increase in plasticity was insignificant; therefore, more research is needed to improve the efficiency of this process.

Materials and Methods

Samples made of 5754 aluminium alloy in the form of a 1 mm thick sheet were used in the tests. The material was delivered in two hardening states: H111 and H22. In order to realize different strain conditions, two types of tests were performed: tensile and deep drawing. An INSTRON 3369 tensile machine was used to carry out the tensile tests with a strain rate of 0.0025 s^{-1}. Tensile samples with a experimentally fitted gauge length of 75 mm and a gauge width of 12 mm, milled along the rolling direction, were used.

The Erichsen 142 Sheet Metal Testing Machine was used to carry out deep drawing tests with a punch speed of 0.4 mm/s. Two operating modes were used to implement the deep drawing process: normal (NL) and sheet holder quick release (SHQR). In the NL mode, a constant blank holder force was maintained throughout the test. In SHQR mode, the blank holder force was immediately reduced from the initial value to zero after reaching the set punch depth value. A punch with a circular section with a diameter of 30 mm and a radius of 6 mm and a die with a diameter of 33.5 mm and a radius of 4 mm were used for the deep drawing process. Three samples of different shapes and dimensions were intended for the deep drawing process. Rectangular sample No. 1 with dimensions of 66 by 12 mm was formed in the NL mode with a blank holder force of 30 kN. Circular sample No. 2 with a diameter of 66 mm was formed in both modes with a blank holder force of 40 kN. Sample No. 3, with experimentally fitted dimensions visible in Fig. 1, was formed in the SHQR mode with a blank holder force of 40 kN. A lower value of the blank holder force was used for sample No. 1 due to its much smaller contact area with the blank holder than for other samples.

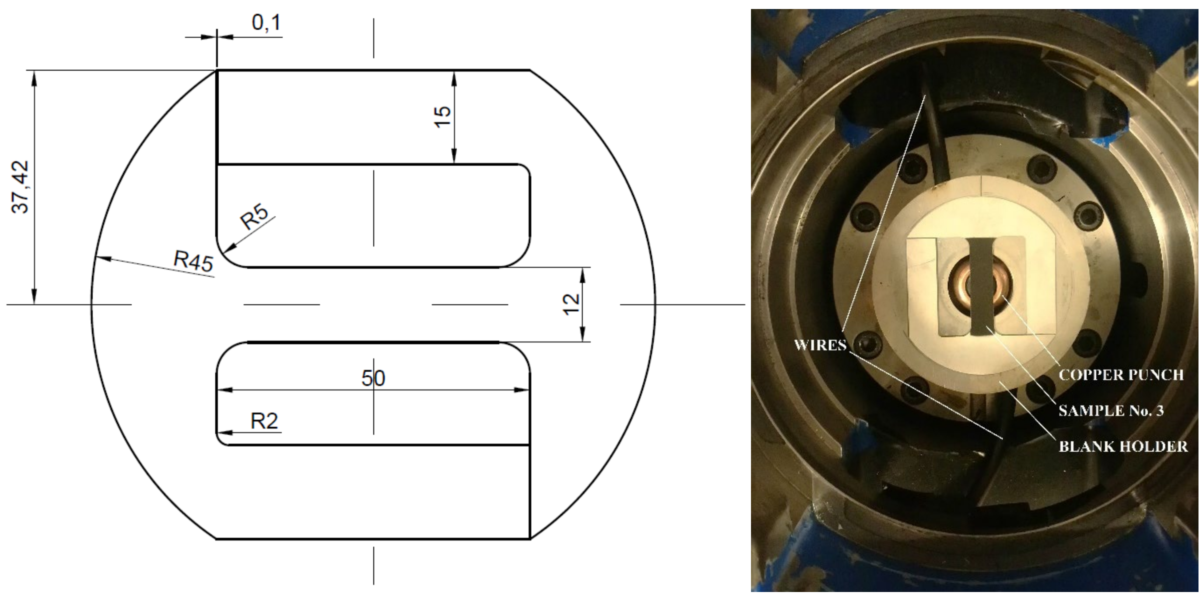

Fig. 1. a) The shape and dimensions (in mm) of sample No. 3; b) Part of the experimental setup with sample No. 3.

The self-constructed current pulse generator operating at a voltage of 2.52 V was used to apply current pulses to the samples during the tensile and deep drawing processes. Important parameters of the power generator also include: maximum value of the pulse current 15 kA and capacity of a bank of capacitors 14 000 F. In the tensile test, current pulses were delivered through electrodes attached to the sample. In the deep drawing test, current pulses were delivered by dies that were also electrodes, as shown in the scheme of the experimental setup (Fig. 2). Dies-electrodes were made of CuNi2Be copper alloy with high conductivity and strength. In order to avoid the flow of current to the machine, insulators are used, visible, among others, in Fig. 2. For this purpose, the screws used to build the experimental setup were also made of non-conductive material. The current was applied in the form of pulsed current generated by a function generator. The pulsed current was chosen because it allows for a greater increase in plasticity than continuous current [9]. The current parameters used were marked in the form p/d, where p is the period and d is the pulse duration. The time p was the time after which the first pulse was applied in the tensile tests.

In the deep drawing tests, the application of pulses began when the SHQR mode was activated or after reaching 3 mm of punch depth (NL mode). The current flowing through the samples was measured using a Rogowski coil and an oscilloscope. The FLIR 440 thermal imaging camera was used to measure the surface temperature of samples previously painted with non-conductive black spray. Each tensile and deep drawing test was repeated three times.

Observations of the microstructure of selected samples were made using a Hitachi H-800 transmission electron microscope (TEM) operating at a voltage of 150 kV. Specimens for microstructure observation were thinned by grinding and then electrochemically polished. Finally, the 3 mm thin discs were ion milled to obtain sufficient quality of specimens.

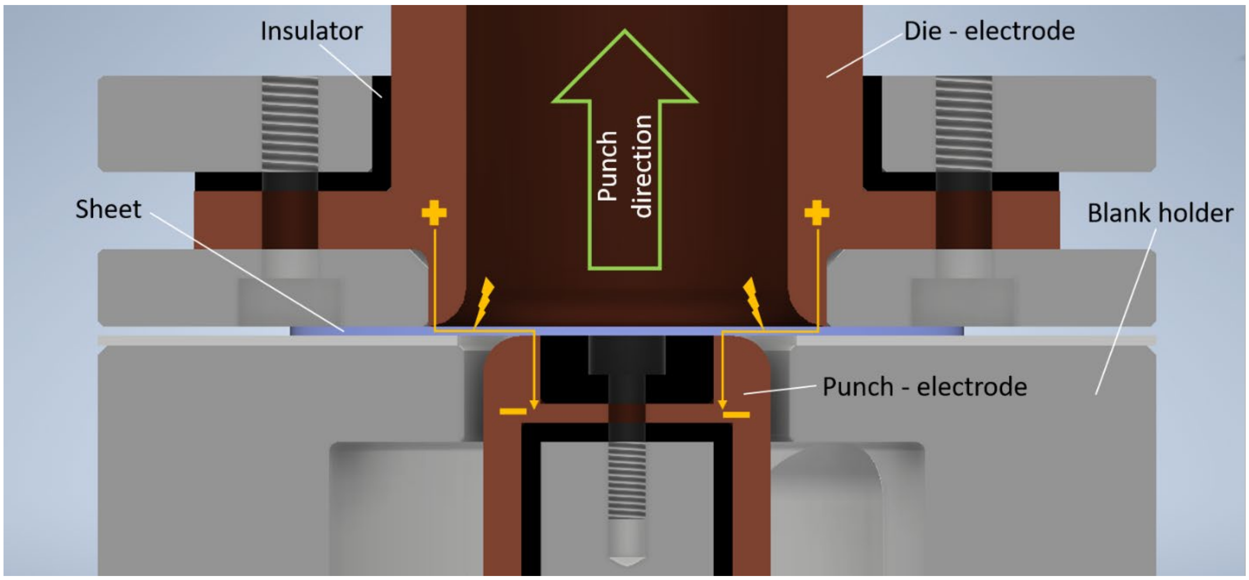

Fig. 2. Scheme of the electrically-assisted deep drawing experimental setup.

Results and Discussion

The engineering strass-strain curves of the aluminium alloys 5754-H22 and 5754-H111 with and without pulsed current application are shown in Figure 3a and 3b, respectively. It is clearly seen that the application of current pulses results in an increase in the total elongation of the 5754 aluminium alloy in both the H22 (by 105%) and H111 (by 48%) states. This is less than that of 5052-H32 aluminum alloy [5], but more than that of 5083 aluminum alloy in various hardening states [16]. When a current pulse is applied, the sample temperature increases significantly. At the same time, the stress value on the stress-strain curve drops dramatically. In this study, the nominal current density (the current value, measured by the Rogowski coil, divided by the cross section area of the sample) was 200 A/mm^2. This drop in stress is mainly caused by thermal expansion and softening due to Joule heating. However, just before the next pulse is applied, the temperature drops almost to the room value [17]. The lack of stress increase to the value corresponding to the curve without the application of current pulse, as well as the increase in material plasticity, is explained by the annealing of the material. The maximal values of the sample surface temperature recorded by the thermal camera are 332 and 295 °C for alloys in the H22 and H111 states, respectively. Nevertheless, according to the localized Joule heat theory, the temperature near grain boundaries and dislocation clusters could have been temporarily higher [7]. Therefore, these were places particularly suitable for recovery and recrystallization processes. It should be noted that the average surface temperature of the sample during the test was less than 150 °C. The sample under the H22 condition achieved a greater increase in elongation, and was intended for further tests.

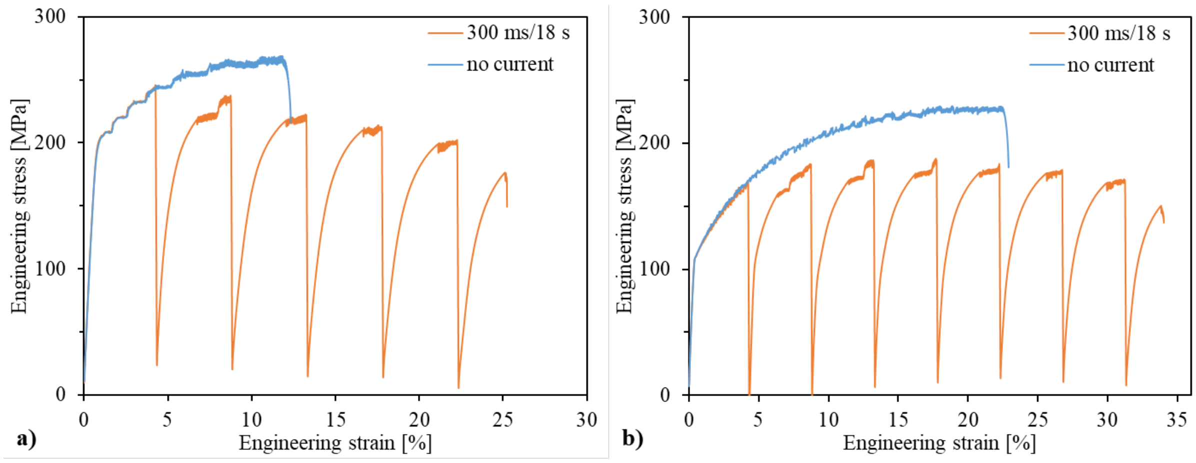

Fig. 3. Engineering stress-strain curves of 5754 AA in the a) H22 and b) H111 state with and without pulsed current application.

Fig. 4a-b presents the force-displacement deep drawing curves (force at punch and punch displacement) for the 5754-H22 aluminium alloy with and without pulsed current application. The force-displacement curves for samples No. 1 and 2 (for both operating modes) are presented in Fig. 4a. There are no visible changes in the course of the curve and material plasticity as a result of the application of current pulses in these processes. The detailed effect of current pulses on the punch depth for samples No. 1 and 2 is shown in Fig. 5a. Note that the stress drops in the curves for selected samples No. 2 and 3 results from their forming in the SHQR mode. A slight but visible 6% increase in punch depth was observed for sample no. 3 (Fig. 5b). The average values of the maximal temperatures recorded during deep drawing tests with the application of current pulses are shown in Fig. 6a-b.

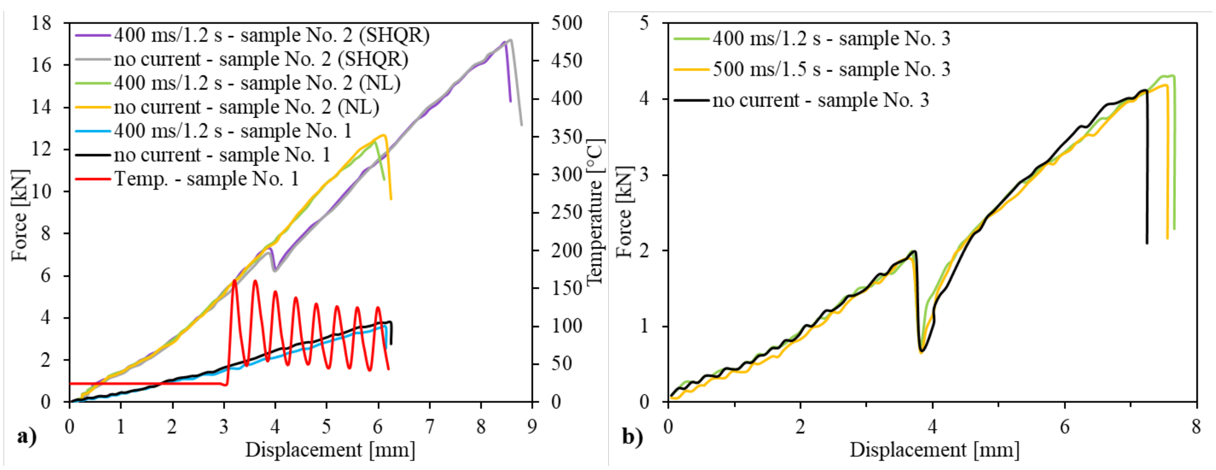

Fig. 4. Deep drawing force-displacement curves of 5754-H22 AA for a) samples No. 1 and 2 and b) sample No. 3 with and without pulsed current application.

The sample temperatures achieved in deep drawing processes are much lower than those of tensile tests, which is the main reason for the slight or no increase in the plasticity of the material. In the case of sample No. 2, its cross-section was too large to obtain a useful current density value. The temperature for sample No. 2 was not greater than 50 °C, and for sample No. 3 it was about 100 °C, which allowed for a slight increase in the punch displacement. Although the temperature of sample No. 1 was the highest (about 150 °C), it did not change the plasticity of the material. This can be explained by the fact that the sample had a small volume and even though it temporarily reached the highest temperature values, it was then immediately cooled. Further research will be conducted, including modifications to the experimental setup, in order to increase the plasticity of aluminium alloys in this process. Making dies from a high-strength copper alloy has the advantage that current pulses can be delivered only to a selected part of the formed sheet. Thanks to this, it is possible to reduce the amount of energy used in the process. Unfortunately, temperature plays a key role in electrically-assisted processes. The small volume of the heated material results in quick heat absorption and thus lower plasticity of the material.

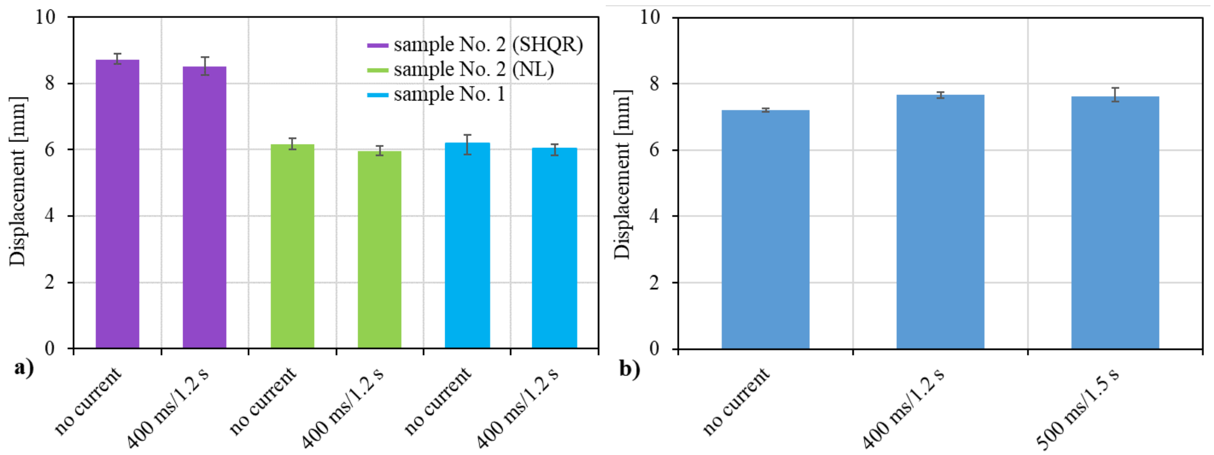

Fig. 5. Influence of current parameters on the height of the drawpieces of 5754-H22 AA for a) samples No. 1 and 2 and b) sample No. 3.

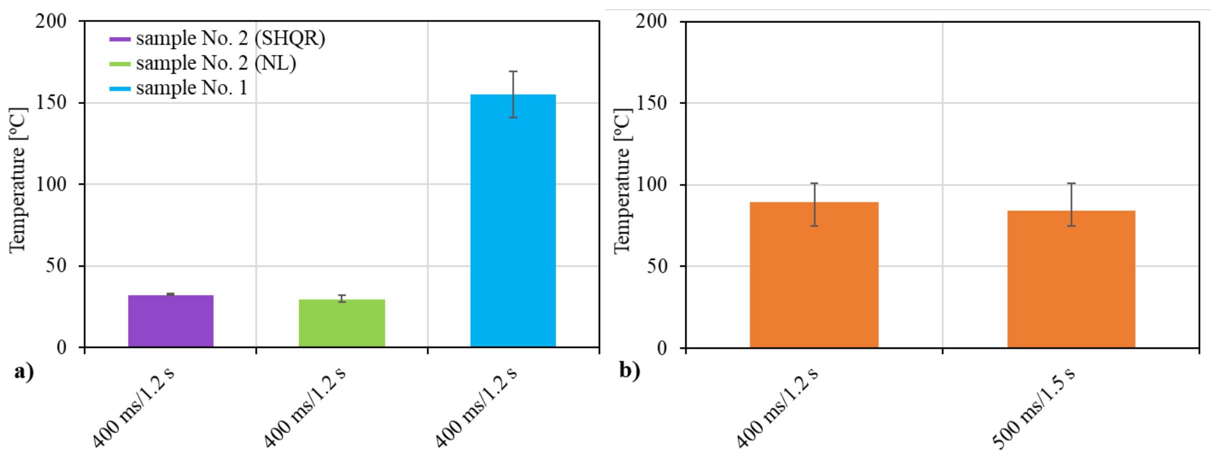

Fig. 6. Influence of current parameters on the maximal temperature of the drawpieces of 5754-H22 AA for a) samples No. 1 and 2 and b) sample No. 3.

The application of current pulses resulted in a significant increase in the plasticity of the 5754-H22 aluminium alloy in the tensile test. Therefore, TEM studies were performed to evaluate the effect of current pulses on microstructure changes. For this purpose, two additional EA tensile tests were performed and stopped after the application of the second and fourth pulses. When the tensile test is stopped exactly after the pulse is applied, it is possible to precisely determine its effect on the microstructure. In addition, a one non-EA tensile test was performed and stopped at the same strain value as the EA tensile test stopped after the second pulse. Specimens were cut from the center of the samples thus obtained for microstructure analysis.

Fig. 7a shows the microstructure of the non-EA sample. Frequently occurring local areas with high dislocation density and the cellular dislocation structure of subgrains are characteristic images of samples after cold deformation. Subgrains formation is a typical feature of materials with such high stacking fault energy as aluminium alloys. On the other hand, subgrains were also recorded in EA samples (Fig. 7a-b, sample after the application of the fourth pulse); however, they were surrounded by low-angle grain boundaries (LAGBs) and not areas with high dislocation density

[18]. The presence of such subgrains with an internal structure with a low number of dislocations or without them is a typical configuration of the material after the recovery process. Single, small grains, identified as newly recrystallized, were also visible on the surface of the analyzed specimen (Fig. 7c). The temperature of the material that occurred (332 °C) and the appropriate amount of accumulated deformation energy were sufficient to start the dynamic recrystallization process (DRX) locally [19]. The application of a current pulse caused the temperature to increase to a value resulting in the initiation of the dynamic recrystallization process. However, this process took too short allow recrystallization to cover a larger volume of material. It is worth noting that the microstructure features indicated in Fig. 7b-d were present in both samples after the application of the second and fourth pulses.

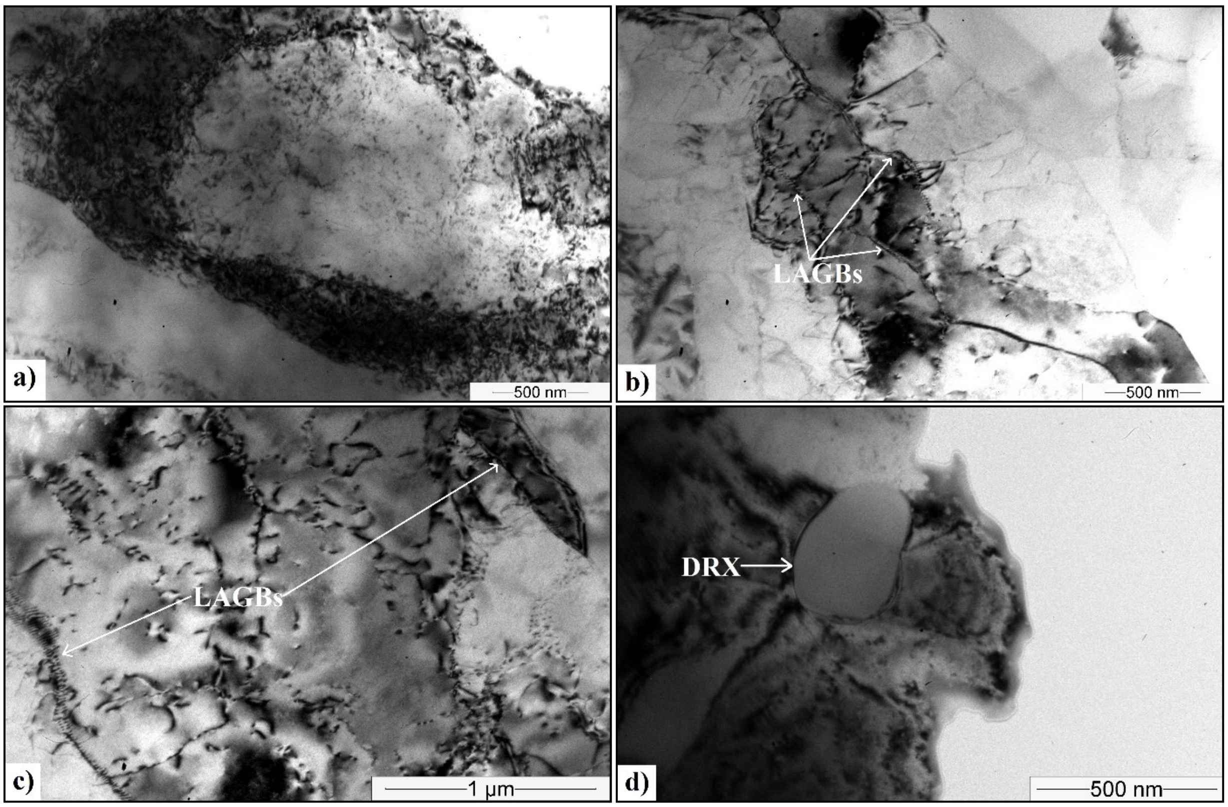

Fig. 7. Bright-field TEM images of specimens obtained from a) non-pulsed, b-d) pulsed tensile tests of 5754-H22 AA.

Summary

The influence of current pulses on the formability of the 5754 aluminium alloy was presented in tensile and deep drawing tests. The research used a new experimental setup (with specially designed dies) to carry out the deep drawing process with the application of current pulses. The study showed that it is possible to significantly increase the elongation of aluminium alloys in EA tensile tests. It is possible to increase the elongation by more than 100%. The main mechanism responsible for the increase in elongation was the dynamic recovery process. TEM studies showed the presence of subgrains surrounded by LAGBs, as well as single DRX grains. However, due to the too low temperature value, the formability of the 5754-H22 aluminium alloy in the deep drawing test increased slightly. These studies showed that 5754 aluminum alloy can be used in electrically-assisted forming technology, in particular in the H22 condition. Unfortunately, due to excessive heat absorption by the tools, their modifications are necessary to increase the plasticity of the material in the deep drawing process.

Acknowledgments
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