Warm Electromagnetic Forming of AZ31B Magnesium Alloy Sheet*

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Abstract

Historically, electromagnetic forming technology has mainly been used to form parts from aluminium and copper alloys due to their excellent electrical conductivity and limited formability by conventional methods. However, little research has been carried out in high strain rate forming of magnesium alloy sheets. Therefore, in the current contribution electromagnetic forming experiments are performed for rolled AZ31B magnesium alloy sheet at different temperatures up to 250ºC.
Two forming operations are studied in this paper, i.e. drawing and bending operations. The final deformations achieved for the different conditions were measured and the effect of both temperature and discharged energy on deformation is shown. Bending experiments at room temperature were recorded by means of a high speed camera and the springback behaviour at high strain rates is evaluated.
In one hand, increasing the forming temperature the yield strength of the material decreases while on the other hand, the electrical conductivity and thus the induced forces are also decreased. It is observed that increasing the forming temperature, for a given discharged energy, the maximum height of the deformed part is decreased. However, increasing the discharged energy at warm temperatures, higher deformation values are achieved without failure. Additionally, bending experiments show that springback effect is also decreased at warm conditions. It is concluded that warm electromagnetic forming is a suitable procedure to manufacture magnesium parts.

Keywords

Electromagnetic Forming, Magnesium Alloy, Warm Forming

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1 Introduction

In last decades there is a clear tendency of reducing the weight of vehicles in the automotive and aeronautic industry [1] due to both fuel economy and environmental concern. New materials with high specific strength, such as high strength steels or lightweight alloys, are being used in order to achieve such lightening. At the present, aluminium and steel are the most frequently employed functional materials in the production industry. However, magnesium alloys are approx. 30% lighter than aluminium and 75% than steel, being the lightest structural material. Therefore the use of magnesium alloys is increasing and it is expected to continue increasing (as reported by the USAMP [2]).

Despite these advantages, limitations such as unsatisfactory corrosion behaviour and a need of suitable forming technologies for magnesium sheets are inherent to magnesium alloys. The lack of formability at room temperature is related with the hexagonal close packed (hcp) crystal structure of Mg and the corresponding limited active deformation mechanisms. One way for increasing the formability of magnesium alloys is to increase the forming temperature owing to the activation of new deformation mechanisms such as non-basal slip systems (e.g. [3]). Therefore, conventional forming technologies are evolving to warm forming processes which owe to considerable increase of deformation as shown by Doege et al. [4] who obtained interesting limit drawing ratio (LDR) of 2.5 for AZ31 alloy.

Another way to increase the formability of magnesium alloys is to employ high speed forming technologies. Research in electromagnetic forming (EMF), despite having been in use since the early 1960's [5], was mainly focused in aluminum alloys (e.g. [6-7]). Very little research has been performed in the field of high speed forming of magnesium alloys. Nevertheless, they all agree that EMF is a promising technology for processing magnesium parts, even at room temperature. At room temperature, Psyk et al. [8] showed the increase of formability and the effect of alloying elements in compression experiments of extruded magnesium tubes. Revuelta et al. [9] performed electromagnetic sheet forming experiments at room temperature. Although they reported an increase of formability, unfortunately, they did not report any value of the deformation achieved. In a previous work by the current author [10] deformation values achieved in AZ31B alloy sheet by EMF were also shown to be higher than the FLC values obtained by conventional forming technologies.

First documented experiments of electromagnetic forming of magnesium alloys at warm conditions can be found in research performed in the former USSR according to [11]. The results show that for the investigated magnesium alloy an extreme increase of the formability was achieved at 200ºC. Uhlmann et at. [11-12] studied electromagnetic forming of magnesium alloys at warm conditions for tubular parts without any reference to the obtained final deformations. Recently, Murakoshi et al. [13] carried out warm EMF experiments for magnesium sheets and they stated that the height of the bulge increased with the increasing of forming temperature.

The electrical conductivity of the material plays an essential role in electromagnetic forming process. The conductivity of magnesium alloys is generally lower than that of aluminum alloys, although it depends on the alloying elements [14]. Nevertheless, the electrical conductivity values of magnesium alloys are adequate for electromagnetic forming process. The most important single factor affecting the electrical conductivity of a metal is the amplitude of the atomic vibration. This factor, in turn, is influenced by the composition of the metal and the thermodynamical variables, such as temperature or pressure. Therefore, when considering warm electromagnetic forming, the decrease of the electrical conductivity of magnesium alloys must be considered since increasing the temperature the induced forces are lower for the a given discharged energy. Accordingly, increasing the temperature the yield stress also decreases at high strain rates as reported in [15] for AZ31B alloy, also employed in this study. Figure 1 shows the evolution of the electrical conductivity (σ_e) and stress values at $\varepsilon_{eps} \approx 0.01$ ($\sigma_{0.01}$) are plotted for different temperatures. Therefore, it is uncertain the effect of temperature on the final deformation for a given discharged energy.

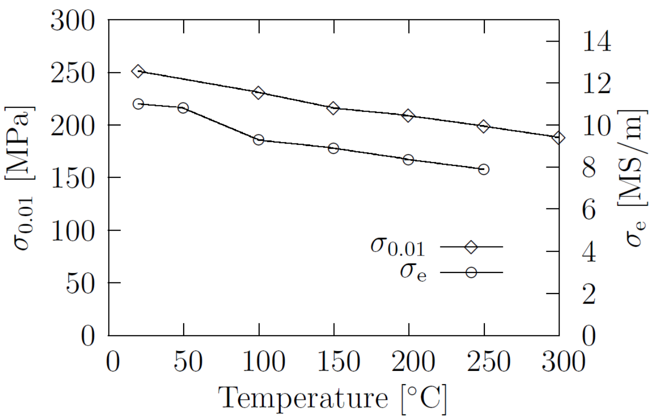


Figure 1: *Effect of temperature on stress values (from Ulacia et al. [15]) and electrical conductivity values (from Avedesian and Baker [16]) for AZ31B magnesium alloy sheet.*

In the current contribution, warm electromagnetic forming experiments were carried out for AZ31B magnesium alloy sheets in order to evaluate the suitability of the technology. Drawing and bending operations are studied at different temperatures up to 250ºC. Finally, texture analysis is performed to show biaxial deformation mechanisms at high strain rates.

2 Experimental Procedures

2.1 Equipment and tooling

Electromagnetic forming experiments were carried out in the laboratories of Labein-Tecnalia. The experiments were conducted using a commercial Maxwell Magneform capacitor bank with a maximum stored energy of 60 kJ. The energy is stored in 30 capacitors, each of them with a capacitance of 60 µF, divided in four independent banks in order to adjust the discharging parameters. The four divisions of the banks are: one group of 3 capacitors (180 µF), 2 groups of 6 capacitors (360 µF) and one group of 15 capacitors (900 µF). The system has a maximum working voltage of 8.66 kV and the number of capacitors and the charging voltage is adjusted in order to control the discharged energy. The closing force between the die and the coil was achieved in all the experiments by means of a 40 Tn hydraulic press.

Photron FASTCAM-APX™ high speed camera was also used to record the deformation of the sample in the bending experiments at room temperature. The sampling rate was 37500 fps. Two different operations were studied in the EMF experiments carried out: drawing and bending operations. The coils and dies used for these experiments are shown in Figure 2.

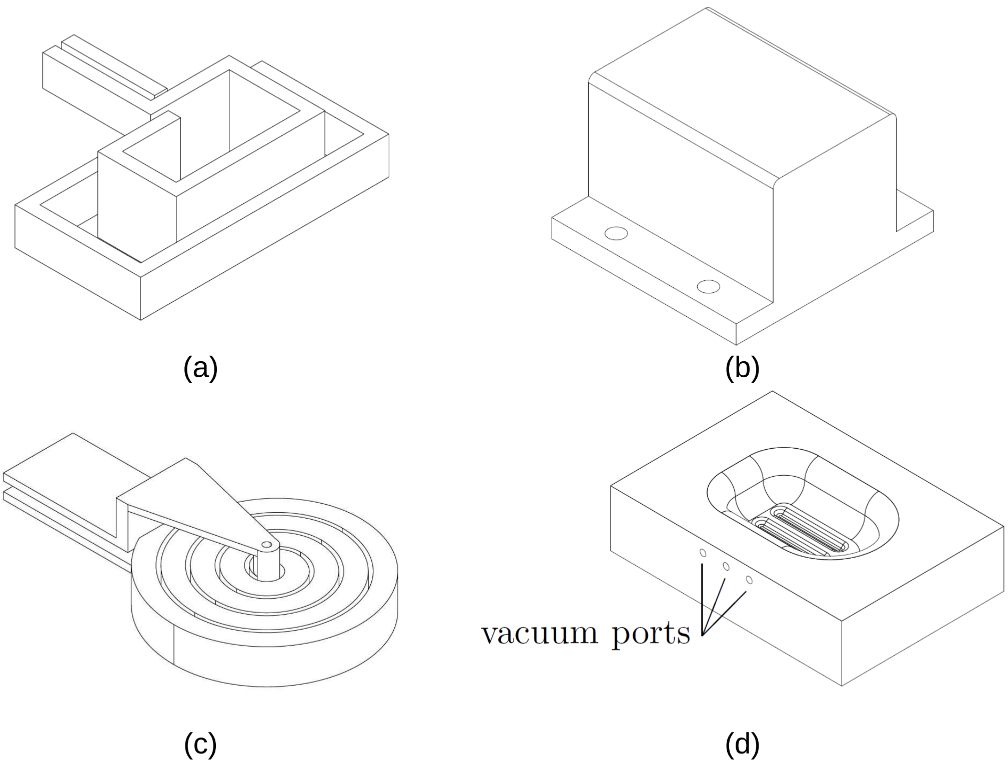


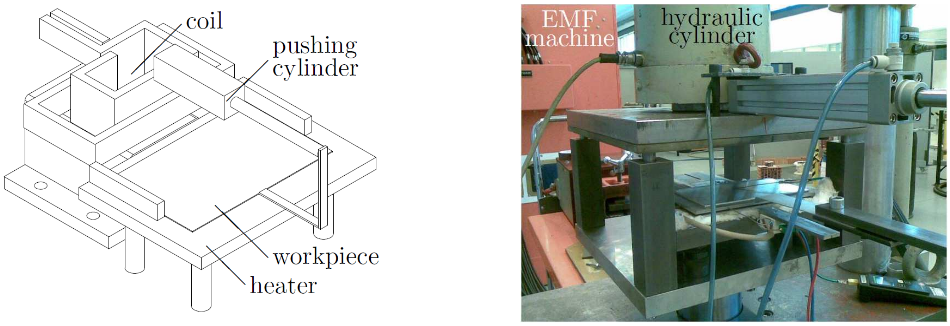
***Figure 2**: Coils and dies used for EMF experiments at different temperatures. (a)-(b) for the bending experiments and (c)-(d) for the drawing experiments.*

In the case of the drawing die, the dimensions were 75 mm width, 20 mm depth and the entry radii were 25 mm. The circular coil used in the experiments is shown in Figure 2(c). The workpiece dimensions were 250 x 175 mm^2. In the bending operation, the dimensions were 175 x 125 mm^2 with a flange of 45 mm. In electromagnetic forming experiments with close dies it is necessary to evacuate the air in the die cavity. Therefore, a vacuum pump is used connected to the vacuum ports of the drawing die (Figure 2(d)).

2.2 Heating Strategy

There are different ways to heat up the specimens that will be formed by means of electromagnetic pulses. One way could be heating up the workpiece in an electric furnace and translating it into the forming stage, taking into account the temperature decrease when contacting the tools. Another way could be to heat the part in the forming position. The coil employed for the forming operation can be used connected to a high frequency electric current pulse source (i.e. inductive heating furnace). This integrated induction heating and forming method allows further automation of the process. It was already patented in the 1960's [17] and also used for warm tube forming by Uhlmann and Hahn [11].

In the current electromagnetic forming experiments, the workpiece was heated by means of 800W electric resistance and it was then automatically transferred to the forming stage as it is shown in Figure 3. The heater is commanded with a PID control of the temperature measured by a thermocouple located on the surface of the heater. However, the temperature of the sample is lower than the one measured in the heater and therefore in the experiments the temperature achieved by the workpiece was measured in six different zones by means of thermocouples glued to the surface of the sheet.



(a) (b)

***Figure 3**: Heating strategy. (a) Schematic view and (b) set up of the device.*

The drop in temperature during positioning, closing and capacitor discharging is measured in order to identify the initial forming temperature. Results are shown in Figure 4. It can be noticed that the sheet is heated up to a temperature approximately 10ºC higher than the nominal temperature (i.e. 100ºC, 150ºC, 200ºC and 250ºC), maintained for 5 min and automatically moved to the forming position. However, the temperature during electromagnetic discharge was not measured by thermocouples (notice that in Figure 4 only the cooling during positioning is measured). One reason for not measuring the temperature with thermocouples is that the electric currents induced in the workpiece would flow through the thermocouples to the data acquisition system. Anyway, the response time of thermocouples is significantly higher than the EMF process time. Therefore, in each experiment the time spent for positioning and closing is measured (the average time was 6.5 s) and in this manner, knowing the elapsed time and the cooling curve for each nominal temperature, the initial forming temperature can be estimated for every experiment (and also for different positions). In the forming zone, the temperature was within $T_{nominal}$ ±5ºC in all the cases studied.

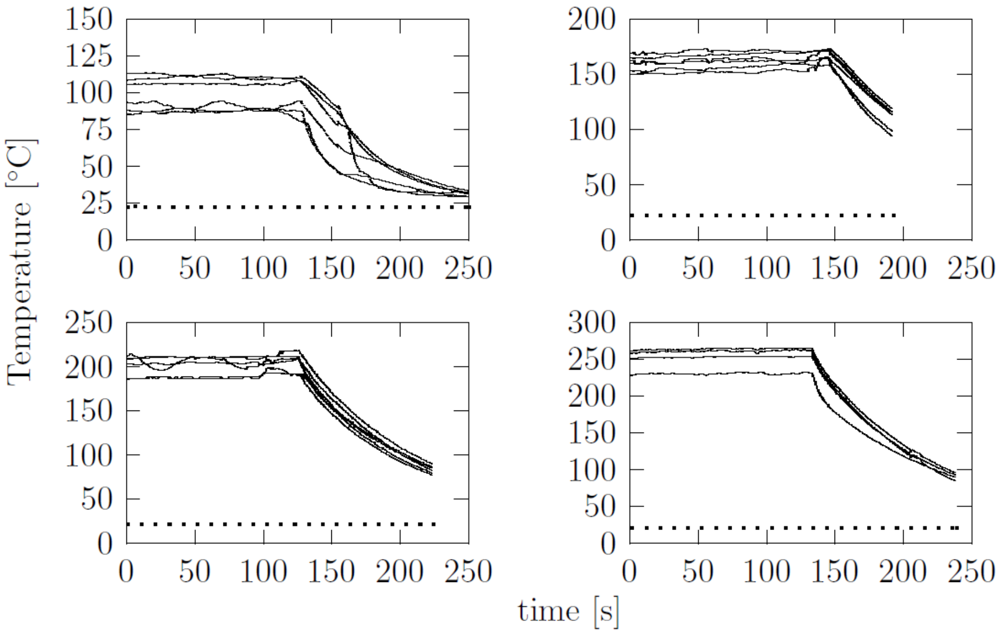


***Figure 4**: Measured heating and cooling curves for different nominal temperatures (dashed lines denote room temperature).*

3 Experimental Results and Discussion

3.1 Drawing operation

Figure 5 shows the influence of the forming temperature and discharged energy. It can be noticed that the maximum height achieved in EMF experiments is decreased when forming temperature is increased for a given discharged energy. The influence of the decrease in the electrical conductivity is slightly more significant than the decrease in yield strength for the temperature range tested. The results obtained in these experiments differ from the results recently reported in [13]. They found that increasing the forming temperature, the height is increased for a given energy (9.8 kJ). However, the material employed in those experiments was annealed at 250ºC for 1 h, whereas the material used in this dissertation was annealed at 400ºC for 2 h. Increasing both annealing temperature and time leads to an increase of grain size and thus, presumably, to a decrease of the electrical conductivity.

The effect of energy on the maximum height achieved is obvious, increasing discharged energy, the height increases for all the studied temperatures. Moreover, it should be remarked that at warm temperatures, a higher energy could be discharged without failure of the workpiece, obtaining better final results. For instance, at room temperature the sample is broken for energies higher than 9 kJ while at 250ºC 15 kJ were discharged without failure obtaining the workpiece completely filling the die cavity. Figure 6 shows the deformed parts obtained at different experimental conditions. It can be seen that the samples deformed at 100ºC (Figure 6(a) and Figure 6(b)) are broken for energies higher than 9 kJ, whereas the sample deformed at 250ºC (Figure 6(c)) completely fills the die cavity without failure. Therefore, warm forming is a suitable strategy for electromagnetic forming of this magnesium alloy because higher deformation degrees than obtained at room temperature can be achieved without a significant increase of discharged energies.

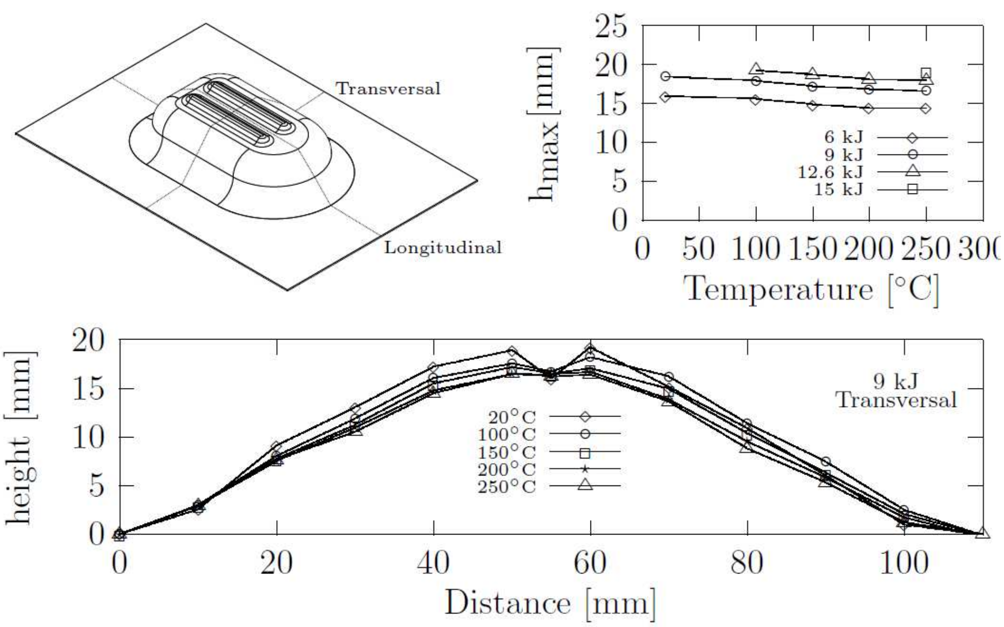
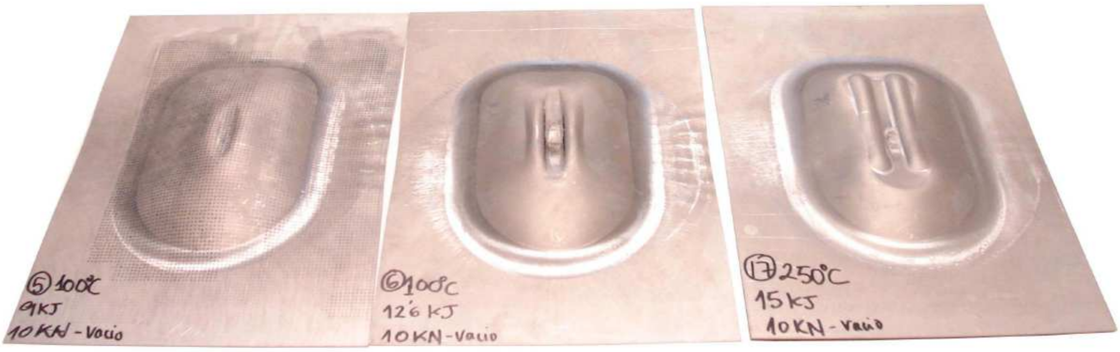


***Figure 5**: Effect of the forming temperature and discharged energy on the maximum height.*



(a) (b) (c)

***Figure 6**: Deformed parts obtained by EMF at different conditions: (a) 100ºC – 9 kJ, (b) 100ºC – 12.6 kJ and (c) 250ºC – 15 kJ.*

3.2 Bending operation

Figure 7 shows the final results of the bending operation experiments for the different discharged energies and temperatures. When analyzing the results, it must firstly be remarked that the deformation achieved was not homogeneous in the whole flange due to the coil geometry and the induced forces for all the temperatures. The repeatability in the experiments was high. The measured angle corresponds to the difference between the final part and the target angle (90º) for an average section of the flange (Figure 7(d)).

At room temperature (Figure 7 (c)-(e)) it is shown that increasing the discharged energy the final angle is closer to the target angle, i.e. the difference is decreased. For the experiments carried out in the current research, it is shown a significant inflection point at a discharged energy of 3 kJ. Therefore, high speed camera was used in order to understand the evolution of the deformation during time at room temperature and different discharged energies (1 kJ, 2 kJ, 2.5 kJ, 3 kJ and 6 kJ). In Figure 8 some pictures of the key deformation states for different discharged energies are collected. The measured angle evolution during time is shown in Figure 9. The first conclusion is that the impact with the die is achieved for a discharged energy between 2.5 and 3 kJ (i.e. for 2.5 kJ discharge the workpiece almost hits the die and for 3 kJ an impact is already filmed). Therefore, the inflection point seen in the final angle at 3 kJ seems to be related with the impact of the flange and the die. Moreover, it can be seen that a springback effect is present in all the experiments. Increasing the discharged energy, the plastic deformation is higher, displacing the neutral fiber and therefore the springback is smaller, as previously seen by Iriondo [18].

Increasing the forming temperature, for a given discharged energy, the induced currents (i,e, forces) are decreased. Consequently, the acceleration of the workpiece will also be decreased and also the impact velocity. Therefore, from the previous results, one may incorrectly conclude that increasing the temperature the springback is decreased as a consequence of lower impact velocities. However, it is observed that the final angle is closer to the target angle (Figure 7(e)). This effect must be understood as a decrease of the springback, since the induced forces and therefore the plastic deformation of the part are expected (as seen in the drawing experiments) to be smaller with increasing the temperature. Springback is dependent on thickness-radius ratio (T/R), Young modulus (E) and yield strength (σ_y) [19]. In the experiments the die radius and the thickness of the sheet were kept constant. Meanwhile, increasing the forming temperature the yield

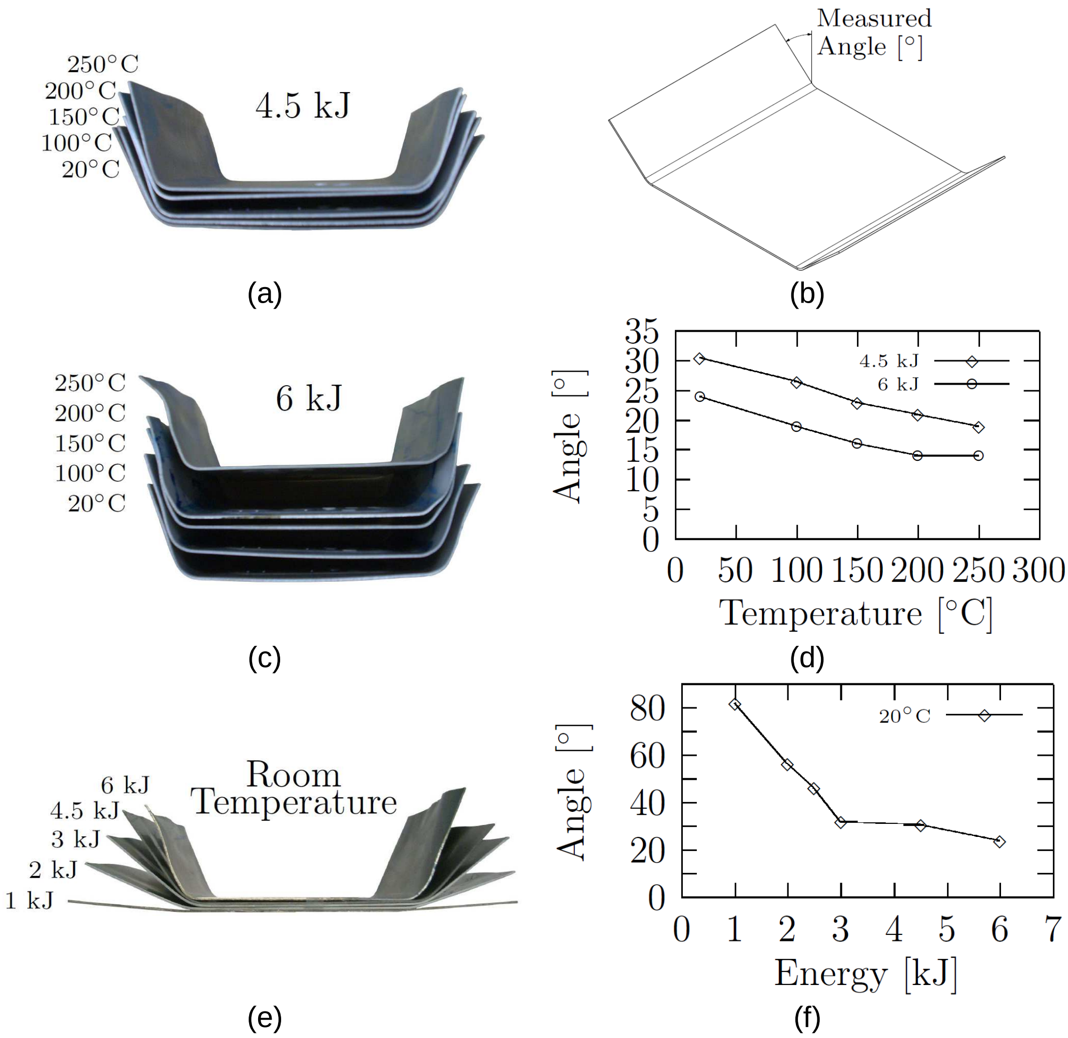


***Figure 7**: Effect of the forming temperature and discharged energy on the bending experiments: (a) different temperatures at 4.5 kJ, (c) different temperatures at 6 kJ (e) room temperature at different energies, (b) measured angle, (d) final angle vs. temperature and (f) final angle vs. discharged energy.*

strength is decreased (Figure 1) and therefore the decrease of the springback can be explained.

4 Conclusions

At warm conditions, the yield strength of the material is decreased while the electrical conductivity also decreases. Increasing the forming temperature, for a given discharged energy, the height of the deformed part is decreased. Therefore, the influence of the electrical conductivity in this type of deformation is more important than the decrease of flow strength. Furthermore, increasing the discharged energy at elevated temperatures, higher deformation values are achieved without failure. Therefore, it is concluded that warm electromagnetic forming is a suitable procedure to manufacture magnesium parts.

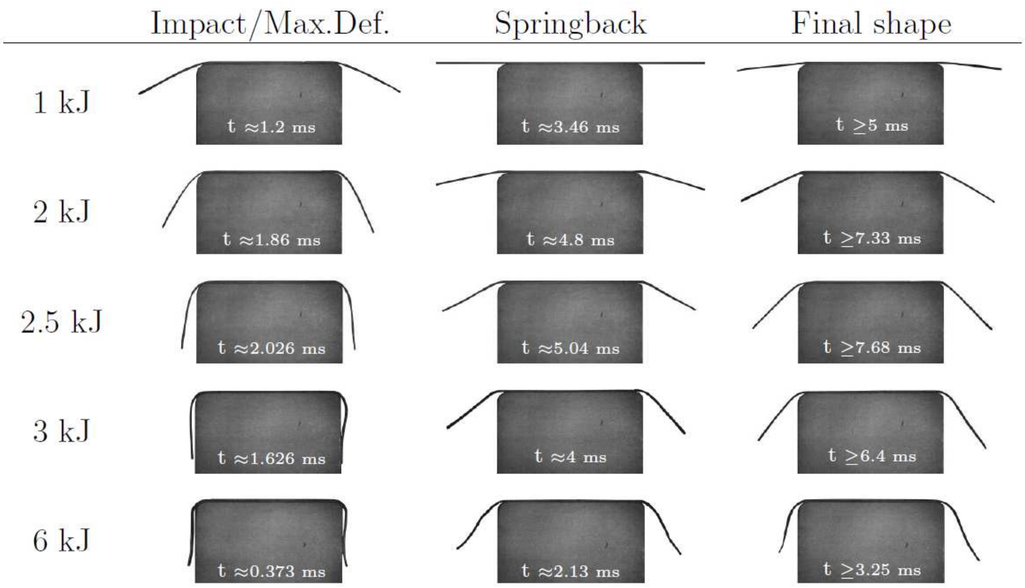


***Figure 8**: Room temperature bending by EMF filmed with high speed camera.*

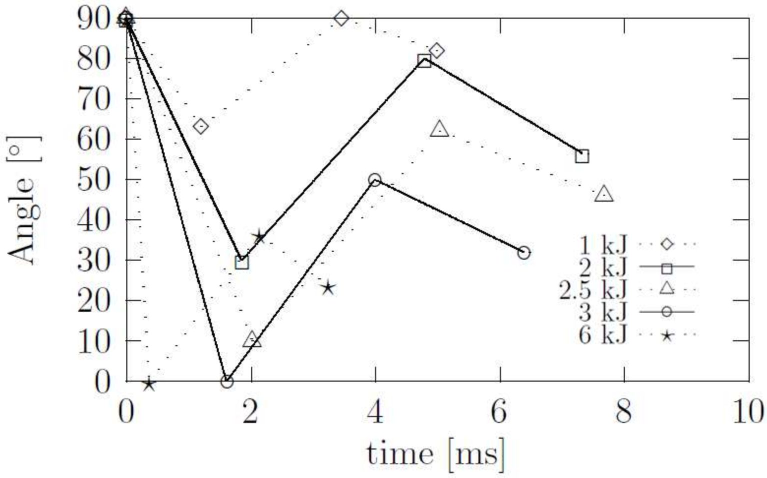


***Figure 9**: Evolution of the bending angle at room temperature (lines are drawn only to guide the eye).*

The springback behaviour at high strain rates is also studied. At room temperature, a decrease of the springback is observed in the samples which impact the die as a consequence of higher plastic deformation. The effect of temperature on the springback is also studied. The final angles achieved in bending operation at warm conditions are closer to the target angle. This can be explained as a reduction of the springback driven by the decrease of the yield strength with the increase of temperature.

In summary, it was observed that the effect of decreasing both yield stress and electrical conductivity with increasing temperature has dissimilar effects depending on the type of the forming operation. In drawing operations, the decrease of electrical conductivity has more influence while in the bending operations where springback is a major factor, the decrease of yield stress is more important.

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