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Proceeding Paper

Direct Resistance Heating of Aluminum Sheets for Rapid Superplastic Forming †

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Abstract: Superplastic aluminum forming is a promising manufacturing process for the transportation industry because it allows for the manufacturing of complex body parts from a single sheet of aluminum, reducing the number of pieces and the weight of vehicles. However, the process is still limited, among other things, by the low heating rate of the sheets. Indeed, for the 5000 series aluminum alloy, a temperature between 450 and 550 °C must be reached, but the furnaces used are inefficient, leading to heating times in the order of ~3 to 6 min. A test bench has been developed to evaluate direct resistance heating as a solution. It allows heating 350 × 200 × 1 mm sheets. The uniformity of the sheet's temperature is an important factor in ensuring good formability and has been evaluated using an infrared camera. Tests show that the sheets can be heated within 20 s using a current of 6200 A, with a standard deviation of about 10 °C over the surface of the sheet.

Keywords: Thermoforming; superplastic forming; aluminum; direct resistance heating

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1. Introduction

The superplastic forming process involves heating a metal sheet to place the material in the superplastic range. Entering the superplastic range allows the material to exhibit high ductility, increasing its elongation at fracture from 15% to over 380% for 5000 series aluminum alloy [1]. This high ductility enables the formation of complex parts, expanding the possibilities for designers and engineers. In a second phase, the sheet is inserted into a press where the application of pressure in the cavity allows the sheet to easily conform to the shape of the mold and, thus, form the part.

However, superplastic forming is limited by the deformation rate during the pressure application and the heating rate. Concerning the heating phase, 5000 series aluminum alloy needs to be heated over 500 °C [2]. Indeed, a correct temperature for forming is between 450 and 550 °C. The current process uses steel plates to heat the sheets by convection and radiation leading to heating times between 3 min and 6 min. To reduce processing and part to part time, the objective is to achieve heating time of less than 30 s using the direct resistance heating (DRH) method.

Direct resistance heating involves passing an electrical current through the material to be formed, heating it through joule effect. In most cases, copper or aluminum electrodes linked to a generator are placed against the sheet to allow current flow [3,4]. This process is already promising, with studies showing it allows heating steel sheets over 800 °C in about 2 s with good temperature uniformity [5]. It is a crucial point in this process to allow uniform ductility over the entire sheet. Along the width, it mainly depends on the current density uniformity, which changes with the contact uniformity of the electrodes and sheet [4]. Furthermore, the process demonstrates an efficiency between 75% and 95% when it is used to heat a steel sheet in a hot stamping process [6].

However, all these promising results were mostly for steel alloys, which have approximately 10 times lower electrical conductivity than aluminum [7]. So, the current flows more easily through it. Thus, for an equivalent current, the heat generation is up to 10 times lower, which requires a more substantial power supply and electrical installation. This process requires much more current intensity to provide the same heating power in the sheet creating an energy-intensive process in the case of aluminum.

This paper presents the development and results of a proof of concept for direct resistance heating in the case of aluminum. In the first stage, the approach involved making heating predictions using theoretical calculations to determine the electrical energy required for the process. In the second stage, these predictions were used to develop a small-scale test bench to validate the operation of the process. Finally, the proof of concept is working well with a heating time of about 20 s and fine temperature uniformity over the surface of the sheet with a standard deviation about 10 °C.

2. Materials and Method

For studying the heating of aluminum sheets using direct resistance heating, the first step was to determine the energy required for heating the sheet. To predict the current required to heat the sheets, a simplified calculation model can be used. All thermal losses are neglected. Electric resistivity varies with temperature to obtain Equation (1):

$$V\rho C_p \frac{dT}{dt} = R(T)I^2, \tag{1}$$

where V is the sheet volume, ρ is the sheet density, C_p is the sheet specific heat, I is the current through the sheet, R is the sheet resistance, and T is the sheet temperature.

Knowing the behavior of the resistance as a function of temperature, it is then sufficient to discretize the equation every second to obtain the average temperature of the sheet over time. Thus, it is possible to know the current required to heat a certain size of sheet in less than 30 s. For example, a sheet of dimension 350 × 200 × 1 mm needs 5000 A to raise its temperature from 22 °C to 550 °C in 30 s. Then, it is easy to evaluate the electrical power required by estimating the voltage with the sheet resistance.

For the second step, a small-scale test bench was developed. It allows heating sheets up to 350 × 200 × 1 mm (Figure 1), about 1/60th the area of 2000 × 2000 × 1 mm aluminum sheets used in production, up to 4000 × 2000 × 2.3 mm.

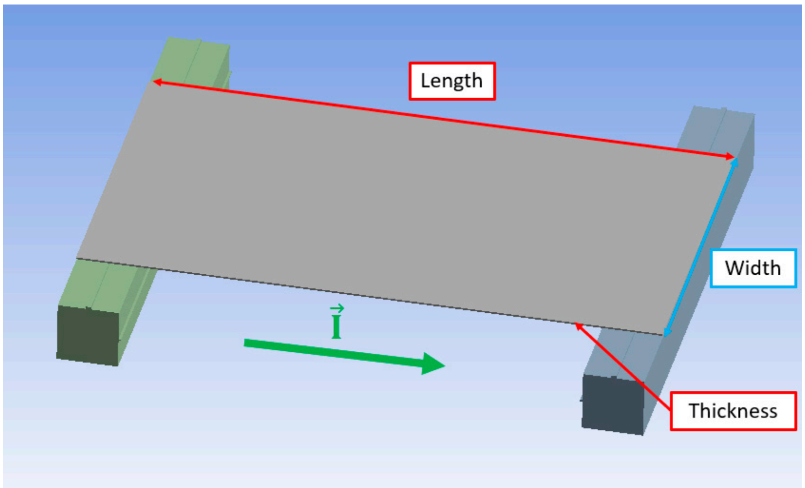

Figure 1. Direct resistance heating concept and sheet dimensions.

Firstly, the main goal of the test bench was to ensure that direct resistance heating was able to heat an aluminum sheet in less than thirty seconds according to the energy predictions. Secondly, the temperature uniformity and energy consumption were essential points to study, which is why sheets of size 350 × 200 × 1 mm were used. They were large enough to observe the impact of the edge effects and temperature homogenization during heating.

The test bench was composed of two 10-ton hydraulic presses, which applied forces on the sheet's fixations (Figure 2a). These fixations were made of two steel I-Beams assembled with a copper electrode centered by four guides (Figure 2b). The electrodes conducted current through the lower surface of the sheet using a lip whose width varied according to the electrode's faces (Figure 3). The sheet/electrode contact is crucial in this application because the temperature uniformity and energy consumption depend on the contact resistance, greatly influenced by the applied pressure and the lip width.

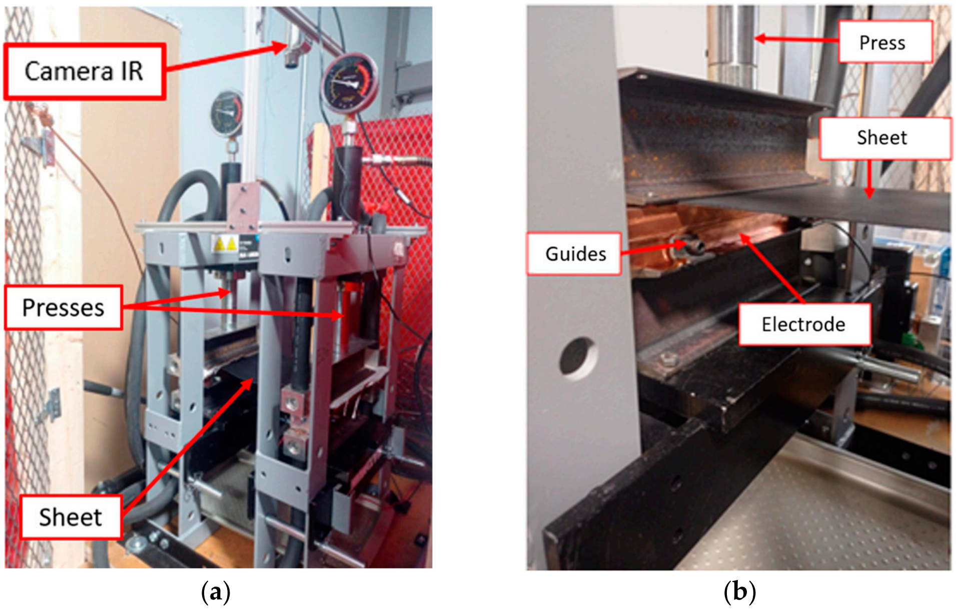

Figure 2. 1/60th test bench. (**a**) Ten-ton presses; (**b**) sheet assembly.

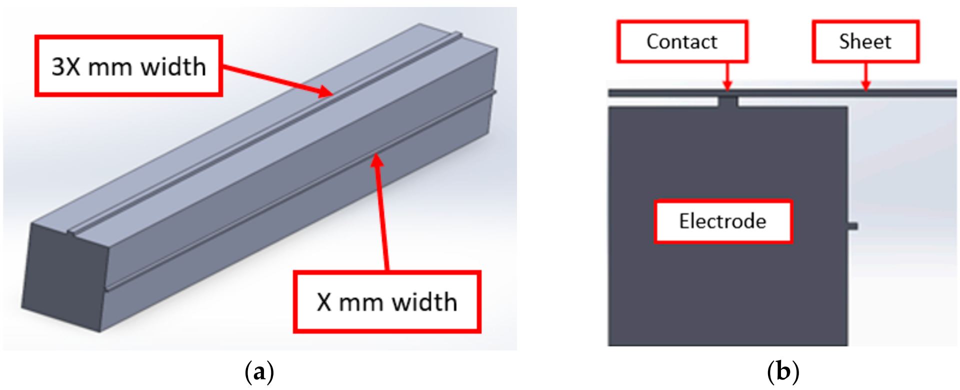

Figure 3. Copper electrodes. (**a**) Electrode's lips; (**b**) electrode/sheet contact.

The electrical power was provided by a 100 kVA transformer, supplied by two phases of a three-phase 600 V plug. A resistance welding controller allows controlling the current intensity according to a percentage of the maximal current. The controller is a dimmer that cut the voltage signal depending on the angle phase value to limit the current value. This setup can provide, in theory, a single-phase current up to 13,800 A through the sheets, but the electrical supply from the building limited this current to 6600 A.

The test bench could take several measurements: (1) the temperature distribution using an infrared camera, (2) the current using a Fluke 376 Clamp Meter, (3) the voltage between electrodes, and (4) the applied pressure indicated by the presses. The infrared camera was an Xi 400 Optris camera, able to measure up to 900 °C surface. The aluminum sheets needed to be painted in black to set a black body emissivity and therefore allow the camera to correctly measure the temperature. Thus, even if the camera field of view was larger than sheet size, only the sheet temperature would be accurate. Snapshots of the temperature distribution from the thermal camera were saved every second, the camera had a 110 016 pixels resolution, and every pixel had an associated temperature. In the same way, the voltage, current, and maximal temperature over time were acquired by an NI DAQ 6008 from National Instrument.

Some parameters could be modified between tests: (1) the current through the sheets, (2) the applied pressure, (3) the electrode geometry (lip width), and (4) the sheet size. For every test, the material used was 5000 series aluminum alloy, the sheets had dimensions of 350 × 200 × 1 mm, and the applied force on the electrode/sheet contact was about 4 U.S. tons. The current through the sheets was about 6200 A, giving a current density of 31 A/mm^2 in the aluminum sheet. Finally, the sheets were heated to 550 °C using the infrared camera, which triggered a threshold in the test program that shut down the electrical power when the sheets reached this temperature. During the sheet cooling, data were still collected to learn more about the temperature homogenization and cooling time.

3. Results and Discussion

The initial tests showed that the bench can heat the sheet to the desired temperature in less than thirty seconds. Indeed, Figure 4 shows the temperature distribution after 22 s of heating, where the maximal temperature of 550 °C was reached, with an average temperature of 535 °C and with a large area above 480 °C. This was close to the calculations, which predicted an average temperature of 630 °C in 22 s and a heating time of 19.5 s to reach 535 °C. The temperature of the beams and electrodes were mostly inaccurate because of the infrared camera adjustment. Indeed, they were not painted in black, and the camera temperature range was set between 150 °C and 900 °C. Figure 5 is focused on the sheet temperature distribution with a narrower temperature scale. It focuses on the main measured area equivalent to a 20 cm square in the sheet's center. It shows a more detailed temperature distribution where the large orange area is between 500 and 550 °C, which is a good temperature for forming. It also enables a first evaluation of the edge effects during the process.

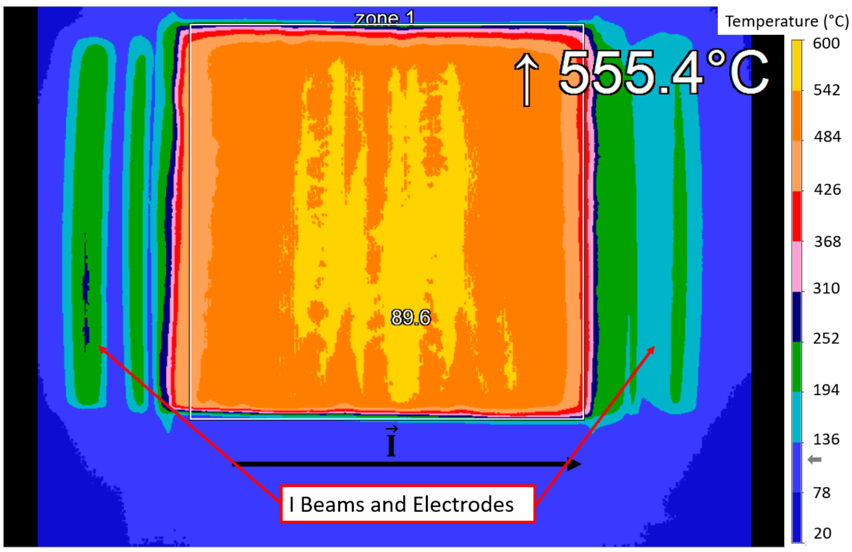

Figure 4. Snapshot of the assembly's temperature distribution after 22 s of heating (OptrisPix software).

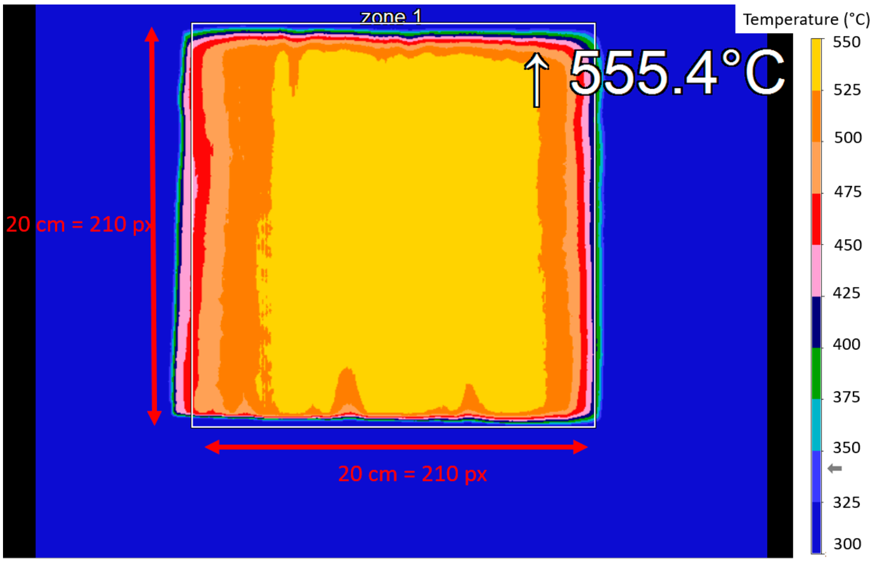

Figure 5. More precise sheet temperature distribution after 22 s of heating (px = pixel).

The temperature uniformity was characterized by post-processing the thermal imaging data. The matrix of the temperature distribution of the main measurement area was obtained with the snapshots taken every second. Then, this matrix was shrunk to a predetermined working area to be formed and to avoid the edge effect in uniformity evaluation. Next, indicators were calculated to characterize the temperature uniformity over the working area: (1) minimal, maximal, and average temperature, (2) area percentage above 500 °C, (3) standard deviation over the total area, and (4) average standard deviations along the length and width, to distinguish the behavior over the different directions.

The selected indicators were estimated every second during the tests and are summarized in Table 1 to enable observation of their evolution over time and to evaluate whether the working area was ready to be formed. By observing the images from the thermal camera, a basic assumption was made to consider the edge effects of 2.5 cm on the sheet's length and 1.5 cm on the width. Thus, the working area in which the temperature values were calculated measured 17 × 15 cm. The results before 18 s and after 26 s are not shown here, as the entire area was under 500 °C.

Table 1. Uniformity temperature results over time.

Time (s)	Tmin (°C)	Tavg (°C)	Tmax (°C)	% Area > 500 °C	σ_{Temp} (°C) [1]	σ_{Lenght} (°C) [2]	σ_{Width} (°C) [3]
18	431	468	485	0	7.6	7.2	3.9
19	456	498	515	51.9	8.7	8.3	4.1
20	465	508	524	82.9	8.8	8.4	4.1
21	480	525	542	97.6	9.3	8.8	4.4
22	488	535	554	99.7	8.9	9.4	4.6
23	474	523	541	96.1	10.3	9.8	4.5
24	462	512	530	85.9	10.6	10.0	4.6
25	450	501	520	66.8	10.8	10.2	4.7
26	439	490	509	17	11.2	10.6	4.8

[1] Standard deviation over the area. [2] Average standard deviation along the length (the standard deviation is calculated for every line of pixels, then, the average of these results is calculated). [3] Average standard deviation along the width (same method as before for every column of pixels).

When the sheet reached its target average temperature of approximately 520 °C, after about 22 s of heating, the uniformity results were good (see Table 1). Almost the entire area was above 500 °C, which means the whole area was above the forming limit temperature. The average temperature was 530 °C with a standard deviation of about

10 °C, so most of the area was included between 515 °C and 545 °C. Furthermore, the standard deviation along the width was significantly lower than the one along the length. This is mainly due to the thermal conduction from the sheets to the electrodes that creates an important loss of heat in the sheet at these locations. It is interesting to note that the standard deviation increased over time, even during the cooling phase. This means that heat diffusion in the sheet does not improve the temperature uniformity. To upgrade it, it is therefore more important to work on the uniformity of the current density. Furthermore, studies already have shown that increasing the current density improves the temperature uniformity [7], leading to the conclusion that the higher the current density is, the faster and more uniformly the sheet will heat up.

It is also interesting to locate areas on the sheet where the temperatures reached did not match the requirements of superplastic forming. In the same way, it is useful to locate areas of minimal and maximal temperature to confirm the thermal simulation of the heating process. A Python program plots a pixel map every second where the area below 500 °C is printed in blue, that above 550 °C is in red, and the remaining pixels are in yellow (Figure 6).

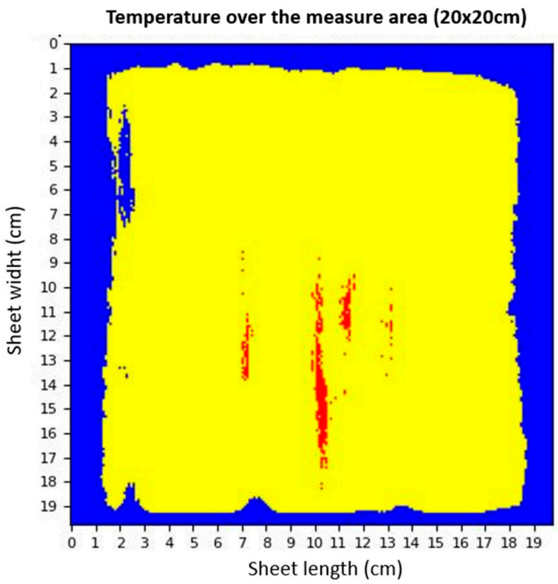

Figure 6. Pixel temperature over the measured area.

It is an easy way to observe the areas ready to be formed those with too low a temperature. For this sheet, the size of the working area was half as long as the initial sheet. The hottest zone appeared in the middle of the sheet where the heat generation was more important. On one hand, the edges along the width of the sheet are more susceptible to cooling by convection, creating an edge effect on the order of one centimeter. On the other hand, the temperature cools down rapidly as one moves away from the middle because the heat generation is less significant there. Indeed, the conduction through the electrodes adds to the natural convection to cool down the sheet. The cooling effects may appear important in comparison with the sheet size. However, simulations and studies have shown that the edge effects do not increase proportionally with the sheet dimension but rather they stabilize [8]. Thus, when the process is scaled up, the ratio between the size of the working area and the sheet's size will be much higher.

4. Conclusions

This study validates that direct resistance heating is a process able to heat aluminum sheets in almost 20 s, thus generating a drastic time saving for the HSBF process. Indeed, the study shows that the process, although still in a preliminary stage, already allows for an adequate temperature uniformity. The process is only limited by the available power so it should be possible to heat faster by increasing the current density and to reach the heating time in the order of 5 s. Moreover, even though the heated sheet size remains limited at this scale compared with the total sheet size, the studies mentioned earlier and our simulations indicate that there is no doubt that for larger sheets, the edge effects will be limited. These results are encouraging and provide a solid foundation for scaling up direct resistance heating to a relevant size for the industry.

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