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# Pulse Current Auxiliary Thermal Deep Drawing of SiCp/2024Al Composite Sheet with Poor Formability

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**The pulse current auxiliary thermal deep drawing (PCATDD) of SiCp/2024Al composite sheets with poor formability was investigated and an integrated high-efficient heating and deep drawing process design was developed to improve the formability of SiCp/2024Al composites. The average pulse current density was achieved at 21.7 A/mm$^2$ with temperature of SiCp/2024Al composites reaching around 673 K in the 50 s. The temperature uniformity of the sheet electrified by the high-intensity pulse current and temperature gradients between the sliding core and top flat of female die were investigated to achieve precise temperature control of sheet and die. During electrification, the stainless steel inserts between the sheet and the copper electrodes successfully prevented heat dissipation and promoted temperature uniformity. Meanwhile, the temperature gradients can be efficiently controlled by blowing high-speed air. The workpiece showed good shape retention, surface quality, and high geometry accuracy. The present study has verified successfully the feasibility of process procedure for PCATDD of SiCp/2024Al composites sheet.**

**Keywords** pulse current auxiliary deep drawing, SiCp/2024Al composites, temperature gradient

## 1. Introduction

The SiC particle reinforced aluminum matrix composites with high specific strength and good wear resistance are utilized in lightweight structures such as framework of airplanes, aerospace, and automobile vehicle (Ref 1, 2). However, a significant disadvantage of these materials is their poor formability at room temperature because of the existence of a large amount of SiC reinforcement particulates. The premature failure is believed caused by a lack of reinforcement/matrix interfacial sliding (Ref 3, 4). In the traditional industry, thermal forming was commonly employed to manufacture the parts with a desired shape, because elevated temperature decrease the sheet flow stress and increase the sheet ductility.

The traditional thermal forming method of heating the sheets via a furnace has many disadvantages, such as the decrease in the temperature of the sheets removed from the furnace prior to forming. The sheets usually need to be heated to a higher temperature because of the heat dissipation. In addition, the sheets exposed to the air suffer a significant amount of oxidation due to the longer heating time. Therefore, reducing the process time and improving heat rates remain the major challenges. As a developing technique, pulse current auxiliary forming technique has arrested the attention of researches for high heating rate and electro-plastic effect, which has been applied to many metal-forming fields such as resistance heating forming technique (Ref 5, 6) and pulse current heating diffusion bonding technique (Ref 7). Therefore, studying pulse current auxiliary forming technique would be worthwhile to because of its remarkable advantages, including short processing time, refined grain, high heating rates, lower energy input, and economic feasibility.

In the present work, we attempted to explore flexible and optimal process parameters to ensure defect-free products. The feasibility of the pulse current auxiliary thermal deep drawing (PCATDD) process was experimentally investigated and relevant results were discussed in detail.

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## 2. Experimental Procedure

### 2.1 Experiment Materials

The experiment used the 17vol.%SiCp/2024Al (providing by Institute of Metal Research of the Chinese Academy of Sciences, Shenyang) composites sheets with high tensile and lightweight. The specimen dimension was 380 mm in length, 105 mm in width, and 1.6 mm in thickness, respectively. The microstructure of 17vol.%SiCp/2024Al composite sheets is shown in Fig. 1. The SiC particles with an average particle size in 3.5 μm were uniformly distributed on the 2024 aluminum alloy matrix. Table 1 shows the strength-to-density ratio of 17vol.%SiCp/2024Al, which reached 198 MPa/(g/cm$^3$) (Ref 8), significantly exceeding that of the other aluminum alloys (Ref 9, 10), and renders the composite appropriate for use in lightweight structure parts in airplanes and aerospace industry.

### 2.2 Pulse Current Auxiliary Thermal Deep Drawing Process

The PCATDD process was implemented to improve the formability of 17%SiCp/2024Al composites sheets. Figure 2 shows the schematic illustration of the PCATDD process, which integrated heating with sheet forming. The sheet was directly set into the dies. The high-intensity pulse current got through the sheet from copper electrode, which generates the tremendous Joule heating. The sheet heating temperature was controlled by adjusting the pulse current intensity. Then, the power was cut off and specimens were immediately deep-drawn. The decrease in temperature before the forming was efficiently prevented because the heating system was directly connected to the forming machine in the whole process design. The transient temperature measurement of the sheet electrified by pulse current was performed using an infrared thermometer. Three groups of temperature measurements were conducted and their results were eventually averaged.

A SWDP-8V/15000A power supply was employed to electrify the sheet via using the low-voltage (a few volts) and high-intensity pulse current (thousands of amps). In order to prevent current leaking, electrical insulated mica layers and ceramic bushings were used to insulate every screw in the electrode and in the hydraulic servo-press system. If current leaking occurred, new electrical paths would be created in parallel to sheet heating system, which could result in disturbing current intensity distribution and thereby reducing heating efficiency. Therefore, it is necessary to check carefully on the electrical insulation for the electrical heating system. During operation process, a hydraulic servo-press system provided forces to secure a better electrical contact between the sheet and electrode, and austenitic stainless steel (SUS304) inserts minimized thermal conduction due to direct contact between sheet and the copper electrode.

The punch, blank holder, and female die were heated to 623 K to achieve high quality of forming of workpiece by electrical heating rods. These electrical heating rods were located in the corresponding hole of die. The temperature of die was monitored using K-type thermocouples, with digital signal feed back to a thermal control system. When die temperature reached a predetermined value, the current of electrical heating rods was automatically turned off, and vice versa. In addition, the sliding core in the female die was designed to provide a gradual force for the shape formation of the bottom of workpiece. High-speed air was blown on the sliding core to attain the temperature gradients. As previously mentioned, the experimental apparatus succeeded to combine the highly efficient heating and deep drawing.

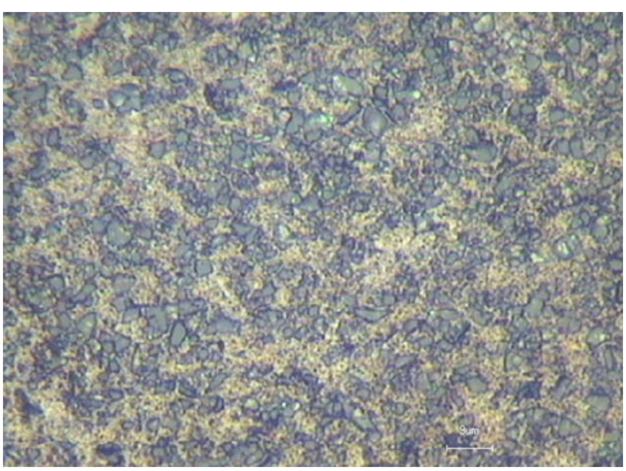

**Fig. 1** Microstructure of 17%SiCp/2024Al composites

## 3. Results and Discussion

### 3.1 Heating Performance of the Sheet Electrified by High-Intensity Pulse Current

The stable and precise control of temperature of the sheet electrified by the high-intensity pulse current is essential because the formability of SiCp/2024Al composite sheet is extremely sensitive to temperature changes. Although the control of the sheet heating temperature is not easy because of

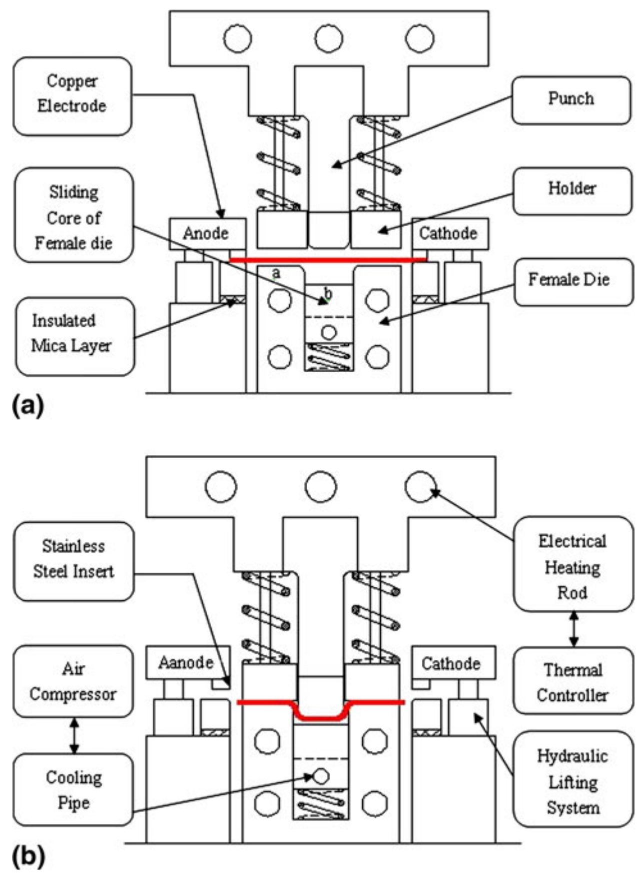


**Fig. 2** Schematic illustration of experimental set-up. (a) Electrifying. (b) Forming

**Table 1 The strength to specific gravity ration of various materials**

| Materials | Tensile strength, MPa | Specific gravity, g/cm$^3$ | Strength/density, MPa/(g/cm$^3$) | Reference |
|---|---|---|---|---|
| 17%SiCp/2024Al | 565 | 2.85 | 198 | Ref 8 |
| Al 2024 | 425 | 2.78 | 153 | Ref 9 |
| Al 6061 | 310 | 2.7 | 115 | Ref 10 |

the rapid heating, the problem was solved by adjusting the input energy. However, an ideal uniform temperature distribution was not achieved because of heat losses and the nonsynchronous temperature increase of the electrified sheet. Nevertheless, approximate the dynamic thermal equilibrium between input energy and heat losses can be achieved, and sheet temperature eventually reached a steady state.

After serial explorations, 673 K was determined as the favorable temperature for PCATDD of SiCp/2024Al composite sheet. When the average current density was 21.7 A/mm$^2$, the temperature of the electrified SiCp/2024Al sheet correspondingly reached a desired temperature of around 673 K under the steady state at the average heating rate of 13.5 K/s. The rate of increase in the temperature of the metal depends on the square of the current intensity per unit area ($I/S$) (Ref 6). Although we believe that higher current density can accelerate heating ratio, higher current density make electrified sheet temperature hard to control. Therefore, the appropriate current density should be use to obtain the approximate the steady state sheet temperature.

Figure 3 shows the average temperature distribution of sheet under an approximate thermal steady state with and without stainless steel inserts between sheet and copper electrode. Firstly, copper electrode was directly applied to electrify the sheet. In Fig. 3(a), a slight temperature difference along the perpendicular direction of current was observed, which can be attributed to higher-rate heating can generate non-synchronous increase in temperature and dynamic thermal transmission among the different area of sheet. Meanwhile, the inverse U-shaped temperature distribution along the current direction can be explained by the number of thermal transmissions caused by the high thermal conductivities of the copper and aluminum alloy because of the direct contact between the sheet and the copper electrodes. On the other hand, the stainless steel (SUS304) with lower thermal conductivities and higher electric resistance was attempted to reduce the thermal transmission between sheet and copper electrode. As Fig. 3(b) shows, the temperature uniformity along parallel and perpendicular directions of pulse current was extremely regulated and the temperature achieve approximately around 673 K. Therefore, the stainless steel inserts, which were used as a heat-insulation layer, was proved quite effective in reducing thermal transmission and obtaining the correspondingly uniform temperature distribution for electrified sheet by high-intensity pulse current.

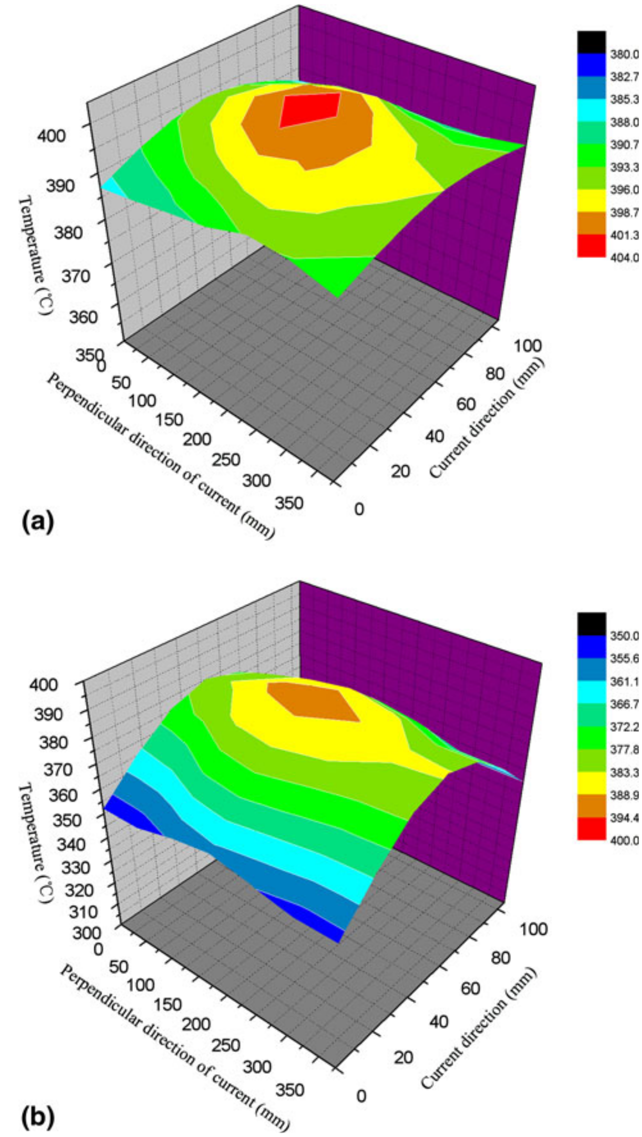


**Fig. 3** Temperature distributions with and without stainless steel inserts between sheet and copper electrodes. (a) Temperature distribution using the bare copper electrode. (b) Temperature distribution with stainless steel inserts

### 3.2 Effect of Temperature Gradient Between Sliding Core and Top Flat of Female Die

Apart from the uniform temperature distribution of sheets electrified by high-intensity pulse current, the die temperature is also one of the important factors to improve the formability of SiCp/2024Al composite sheet. Punch, blank holder, and female die were supposed to heat up to 623 K, but a non-synchronous temperature increase occurred because of heat diffusion and conduction. The average temperature of top flat (Face a) and sliding core (Face b) of female die were recorded based on Fig. 2(a) and the results are shown in Table 2. The average temperature of top flat ($T_a$) and sliding core of female die ($T_b$) reached 629 and 643 K, respectively. It has well known that higher temperature in the top flat of female die can minimize deep drawing force in the flange and oppositely lower temperature in the sliding core of female die can provide the strong transmittable force for the thermal deep drawing of the workpiece. Therefore, a further improvement can be achieved by creating an additional temperature gradient between the top flat of female die and the sliding core instead of uniform temperature.

Table 2 exhibits the temperature gradients can be achieved by blowing high-speed air on the cool pipe in the sliding core of female die. The temperature of top flat is closer to the predetermined temperature (623 K) after blowing high-speed air for 60 s in comparison with 30 and 90 s. Meanwhile, a temperature gradient of 32 K was observed between the sliding core and the top flat of female die after blowing for 60 s.

### 3.3 Forming Performance of Workpiece by PCATDD

The PCATDD of the SiCp/2024Al composite sheet was performed to evaluate the feasibility of the whole process design. Firstly, water-based graphite was uniformly sprayed over both the surfaces of rectangular sheet to maintain its

**Table 2 Temperature gradients between the sliding core and the top flat of female die**

| | Before blowing air | After blowing air | | |
|---|---|---|---|---|
| | | 30 s | 60 s | 90 s |
| $T_{top\ flat}$ (K) | 629 | 628 | 624 | 615 |
| $T_{sliding\ core}$ (K) | 643 | 600 | 592 | 578 |
| $\Delta T$ (K) | 14 | −28 | −32 | −37 |

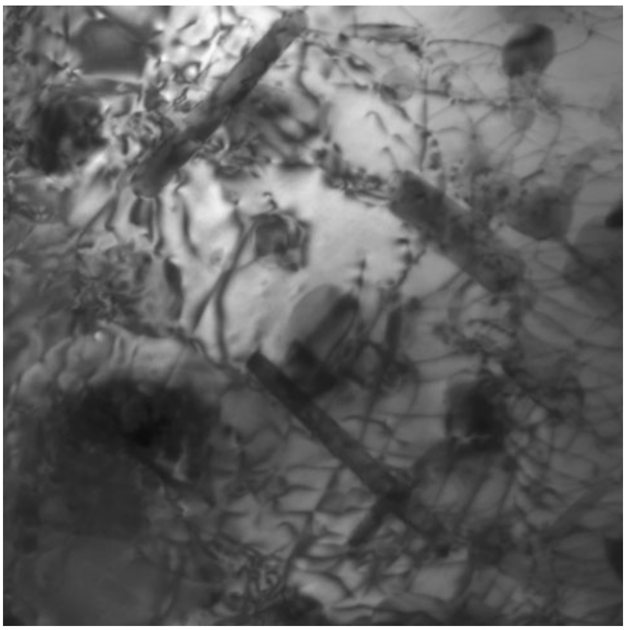

**Fig. 4** TEM image of the workpiece formed in furnace

lubricating properties during the forming process. As one of the important parameters, lubrication can decrease the friction between sheets and die, make the workpiece get good surface quality and increase lifetime of die by reducing wear. Meanwhile, the stainless steel SUS304 inserts, 30 mm in width and 8 mm in thickness, were employed to minimize the heat transmission resulting from direct contact between copper electrode and sheet, while the temperature gradient also were utilized to facilitate deep drawing of workpiece. In addition, the average current density was 21.7 A/mm$^2$, and the electrified SiCp/2024Al sheet temperature by the high-intensity pulse current correspondingly arrived at around 673 K in the 50 s. The forming speed is around 4 mm/s, and the whole forming were finished within 8 s. The workpiece eventually was successfully deep-drawn without decrease in temperature.

As for the microstructure of work piece, Fig. 4 shows a TEM image of the workpiece deformed in the furnace. The typical morphologies of the motion of dislocation in the flange and the force transmission area of workpiece formed via by PCATDD are observed in Fig. 5, respectively. According to the results, TEM image of the work pieces deformed in furnace shows interlaced and disordered dislocation lines. By contrast, TEM images in Fig. 5 exhibit that the dislocation lines have a distinct tendency to arrange regularly and in parallel. Zhang and Tang (Ref 11) suggested that electrons exert a force to dislocations, which lead to the movement of dislocations and

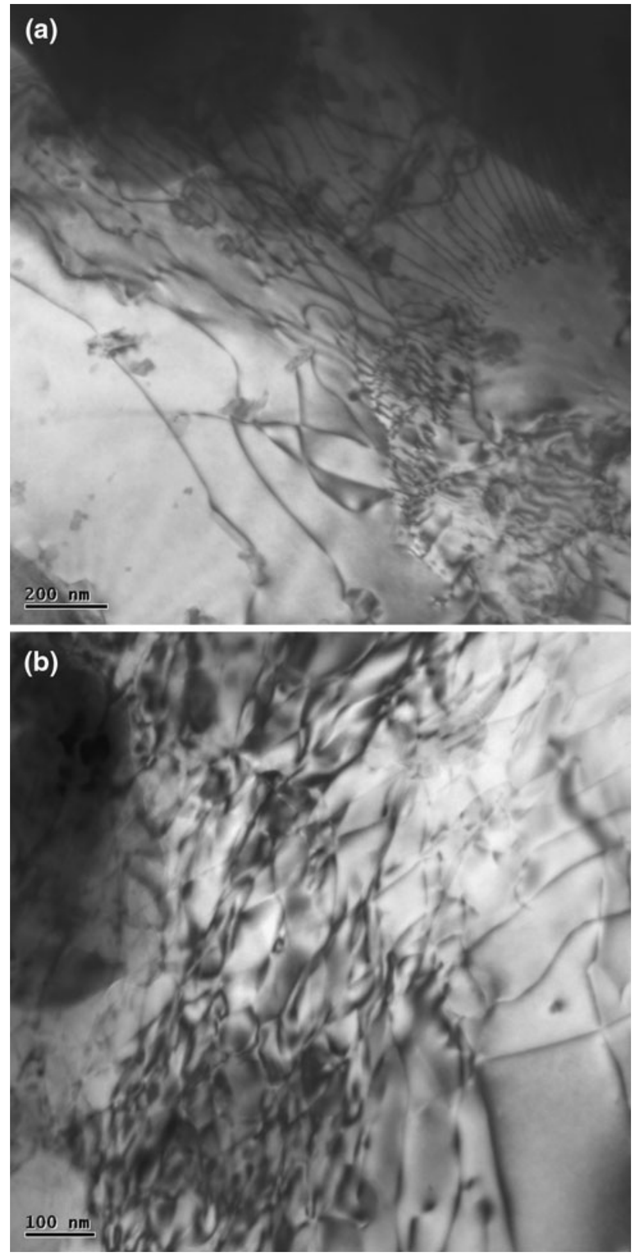


**Fig. 5** TEM images of the workpiece produced via pulse current auxiliary forming (a) flange and (b) force transmission area

their homogeneous distribution. Conrad and Xu et al. (Ref 12, 13) reported on thermal and athermal effects of high-intensity pulse current on plastic deformation. Thermal effect can be ascribed to Joule heat. However, the exact mechanism of athermal effect is still not very clear. One of the possibilities of athermal effect is that results from the additional electron wind force, which pulse current electron exert on a dislocation.

Figure 6 shows the workpiece of SiCp/2024Al composites formed via PCATDD. The workpiece exhibit good shape retention, surface quality, and high geometric accuracy. Fluoroscopy measurements did not reveal any microcracks in the workpiece and the error in dimension was in the range of −0.2 to 0.2 mm. Therefore, the previously mentioned consequences verify the feasibility of the PCATDD procedure and confirm the potential perspective for the current auxiliary forming

**Fig. 6** Finished workpiece formed via PCATDD

technique to form workpiece with the complex geometric framework and poor formability.

## 4. Conclusion

1. The average current density achieved 21.7 $A/mm^2$ and the corresponding temperature of SiCp/2024Al composites sheet reached to approximate 673 K with an average increasing rate of 13.5 K/s.
2. The austenitic stainless steel inserts with low thermal conductivities and high electric resistance as a heat-insulation layer were quite effective to prevent the heat dissipation and promote temperature uniformity of sheet during electrifying.
3. The 32 K temperature gradient between the sliding core and top flat of female die can be effectively actualized by blowing high-speed air in the sliding core of female die.
4. The workpiece of SiCp/2024Al composites was successfully formed via PCATDD at a temperature of around 673 K. Moreover, the workpiece showed good shape retention, surface quality, and high geometric accuracy.

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