

## CNT/2009Al Aluminum Matrix Composite Sheet Forming for a V-Shaped Skin Part

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**Abstract.** The carbon nanotube (CNT) reinforced aluminum sheet with 2.0 mm thickness was hot rolled. The friction stirring process (FSP) was applied to make the reinforcements dispersion uniform. A finite element simulation was conducted to optimize the forming parameters of a V-shaped skin part. It should be formed in two passes, and the bottom corner radius is advisable to be greater than  $R = 30$  mm in the first pass. The V-shaped skin part was successfully formed and the profile accuracy error was less than 0.2 mm. The part's mechanical properties show that the composite sheet still keeps a high strength after two thermal procedures.

### Introduction

Tremendous interests in Carbon Nanotube (CNT), used as the reinforcement material in aluminum composite fabrication, have been widely cognized, such as its high modulus, high tensile strength and low density [1, 2]. CNT tends to tangle in composite [3]. The friction stirring process (FSP) is an effective methodology to make reinforcement phases uniform in composite [4, 5], which is a solid-state processing methodology accompanied by severe plastic deformation and low heat input [5]. The process with embedded CNT in grooves and holes remains fabricated composite sheet in sample size level and the full particles volume fraction introduced difficultly. However, some improving processes were applied, such as particles with a volatile solvent, a thin layer preventing from particles overflow [6]. It effectively fabricates CNT reinforced composite by combining powder metallurgy with FSP [7, 8]. It can realize a sizeable composite sheet followed by extrusion and rolling. Although CNT improves the mechanical properties of composites, especially the strength. Usually, the formability tends to be low [5]. Low formability causes forming complicated [9]. Fewer investigation on CNT reinforced composite sheet forming. A suitable forming process is required. In this work, a large composite sheet was fabricated by extrusion, FSP and rolling after powder metallurgy. To solve the low formability of composite sheet, the thermal forming process was applied to form a CNT reinforced aluminum composite (CNT/2009Al) V-shaped skin part.

### Material Fabrication

#### Hot rolled CNT/2009 sheet

3 vol.% CNT/2009Al composite ingot was prepared by powder metallurgy. The ingot was heated to 450 °C and preserved for 4 hours. It was extruded at 300 ~ 350 °C with an extrusion rate of 16:1. The extruded strip has the good surface quality and no visible micro-cracks. The friction stirring process (FSP) was applied to improve the reinforcement dispersion uniformity in an ingot. The stir pin rotates at 1200 rpm, following a running speed of 100 rpm. The stirring pin is applied with the optimum dimensions of needle length 5 mm, shoulder diameter 15 mm, root diameter 8.11 mm. The overlap rate between the last pass and the previous pass is 50 % to ensure that FSP processes each

region. The FSP operated strip is shown in Fig.1 (a). The composite material was required to be rolled to obtain the required thickness of the plate. The FSP strip was kept at 450 °C for 3 - 5 h, followed by hot rolling. The rolling reduction of each pass is no more than 12 %, and the plate was placed in the furnace at 450 °C for at least 30 min after each rolling. Fig. 1 (b) shows the surface quality of the plate at different thicknesses. The sheet with 2 mm thickness was finally rolled.



(a) FSP operated extrusion strip



(b) hot rolled sheet

Fig. 1. Hot rolled sheet

**Mechanical Properties.** Material strength and elongation directly reflect formability. The mechanical property was tested at high temperature, 400 °C, 450 °C, 500 °C, 525 °C, and different strain rates, 0.01 s<sup>-1</sup>, 0.1 s<sup>-1</sup>, 1 s<sup>-1</sup>, 3.0 s<sup>-1</sup>. Specimens were received by cutting from the fabricated composite sheet in the rolling direction. The dimensions of specimens are shown in Fig. 2. The INSTRON 5450 high temperature testing machine was used. Fig. 3 shows the true stress-strain curve of the rolled sheet. It can be seen that the true strain increases as strain rate increases. The tensile strength and true strain are 121 MPa and 0.5 at 400 °C, 38.6 MPa and 0.68 at 500 °C. It shows that formability of CNT/2009Al improves as temperature and strain rate increases in the range of investigated conditions.

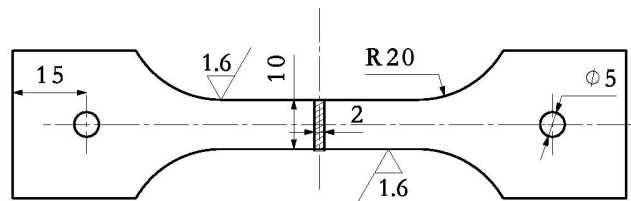
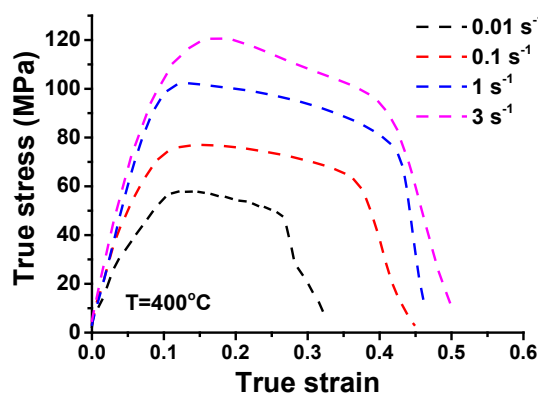
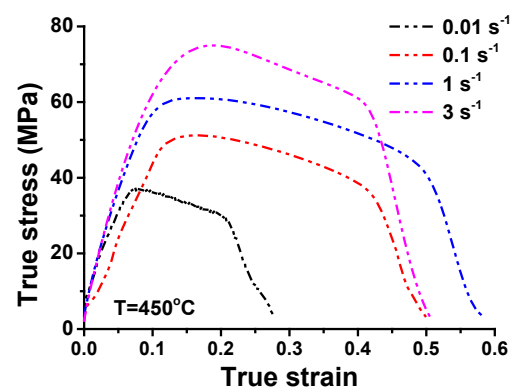


Fig. 2. The specimen dimensions applied in thermal uniaxial tension test



(a) 400 °C



(b) 450 °C

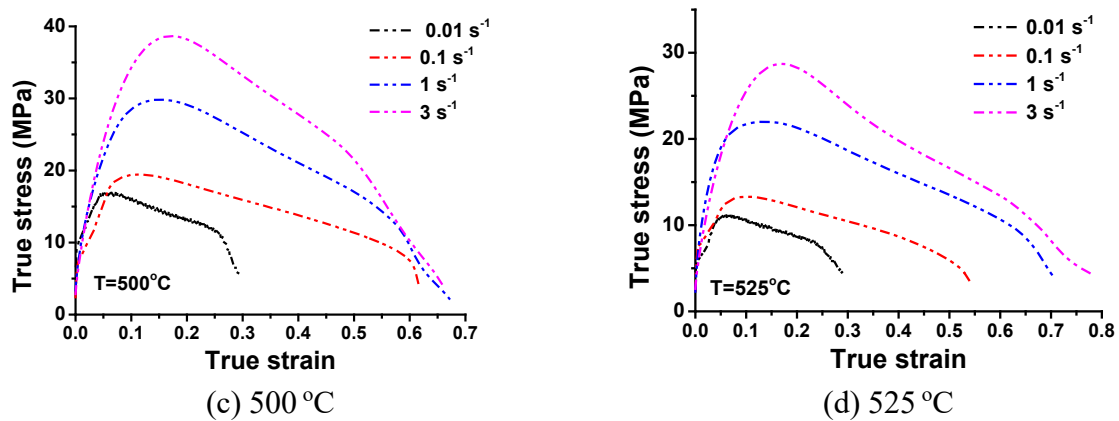


Fig. 3. True stress-strain curves of CNT/2009 composite sheet

### Forming Parameters Research

Forming simulation of a V-shaped skin part was conducted using commercial finite element code ABAQUS to determine the processing parameters, such as temperature, forming passes, tooling structure, et al.

In Fig. 4 (a), the punch runs from the initial state to the die until molds close. Due to that there is no constraint of blank holder in the forming process, both sides of the sheet are upwarped, which is shown in Fig. 4 (b). The blank was pressed until the die was closed. The corner area tends to be dangerous rupture due to the small radius, which causing the severe deformation.

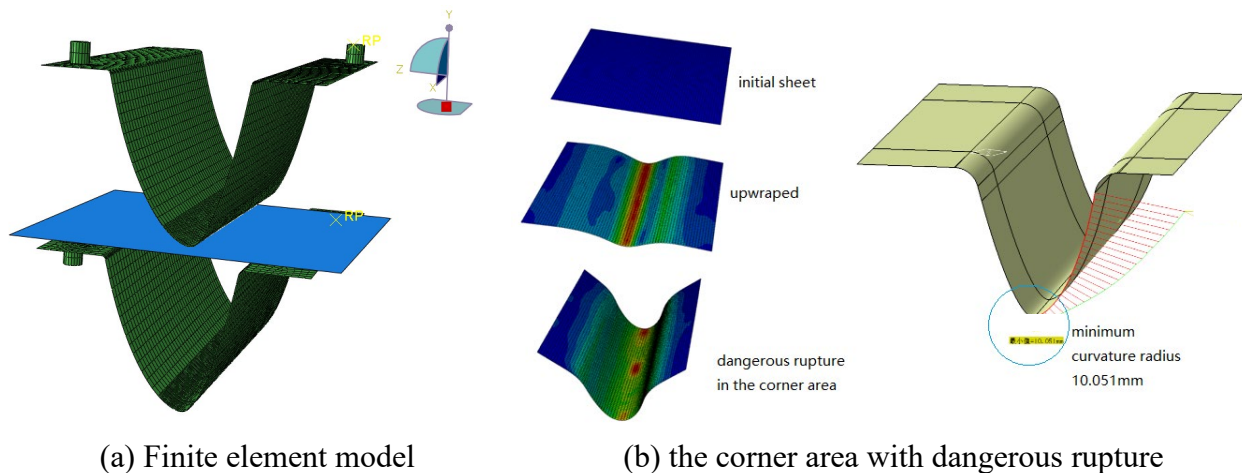


Fig. 4. Finite element model for V-shaped skin part

The forming temperature was set to 450 °C, 500 °C and 525 °C, and the stress distribution at different temperatures was analyzed in single pass forming, which is shown in Fig. 5. The strength of the rolled composites sheet is 52 MPa, 20 MPa and 14 MPa at 450 °C, 500 °C, 525 °C and strain rate of  $0.1 \text{ s}^{-1}$ , respectively. As can be seen from Fig. 5, stress concentration is serious at corner area and flange area in single pass forming, and the stresses reach the limit. Risk points of fracture occur in both areas. The curvature radius of the bottom corner in the final state is approximately  $R = 10 \text{ mm}$ . The severe deformation will appear here. The blank flange is left as process allowance. Therefore, the key control in forming focuses on corner area.

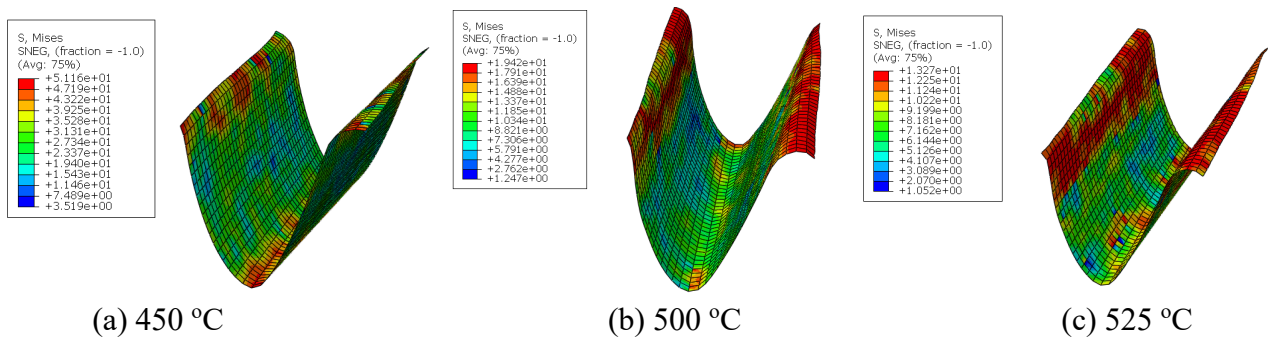


Fig. 5. Stress distribution in single pass forming

The forming process will be divided into two passes. It requires enlarging the bottom corner radius, namely preformed a large corner. The corner radius in the first pass is optimized to  $R = 30$  mm to reduce stress concentration. The formed part in two passes is shown in Fig. 6 (b) and Fig. 6 (c). The stress is under the limit, denoting that it can be formed safely in two passes at 500 °C.

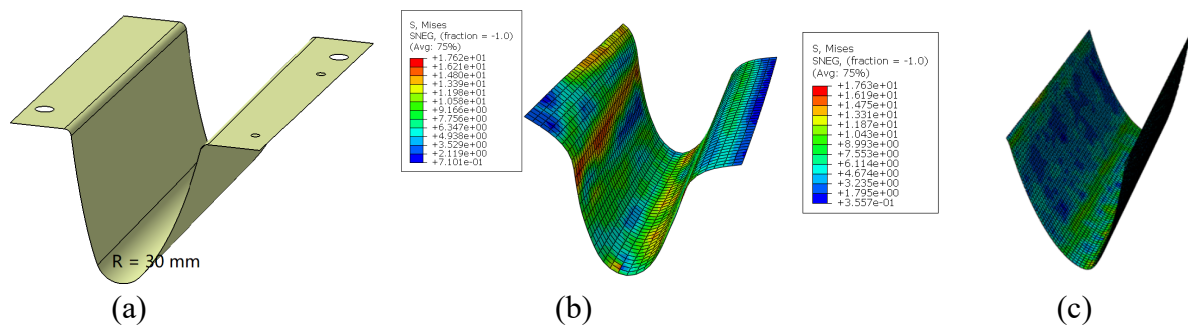


Fig. 6. Stress distribution. (a) Corner radius optimized to  $R = 30$  mm in the first pass; (b) stress distribution in the first forming pass; (c) stress distribution in the final forming pass

## Experimental Investigation

According to the optimization, the tooling was designed for two passes. The bottom corner is  $R = 30$  mm in the first tooling and the final surface profile will be in the second pass. Followed by blanking and lubrication coating, the thermal forming process was carried out in 100 t punching equipment. In each pass, temperature was set to 500 °C and preserves 10 minutes for preheating and reducing springback. The V-shaped skin part was successfully formed, which is shown in Fig. 8.

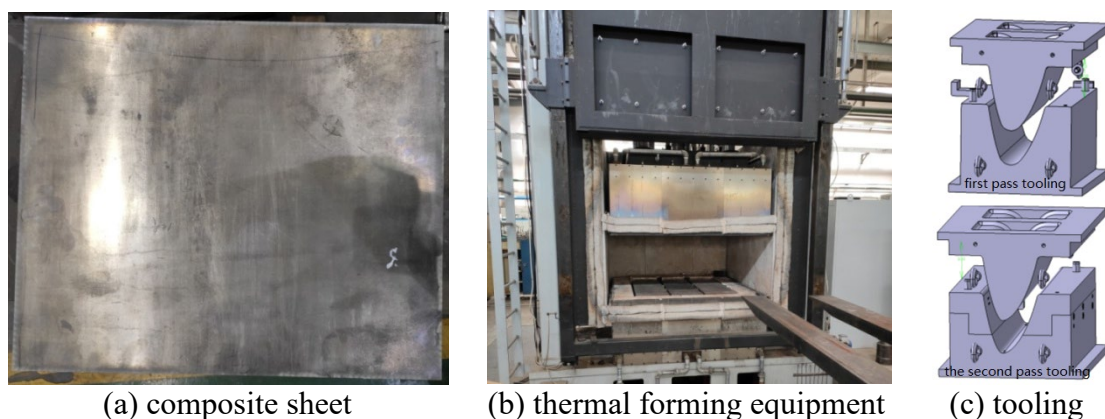


Fig. 7. Composite sheet blanking and 100 t thermal forming equipment



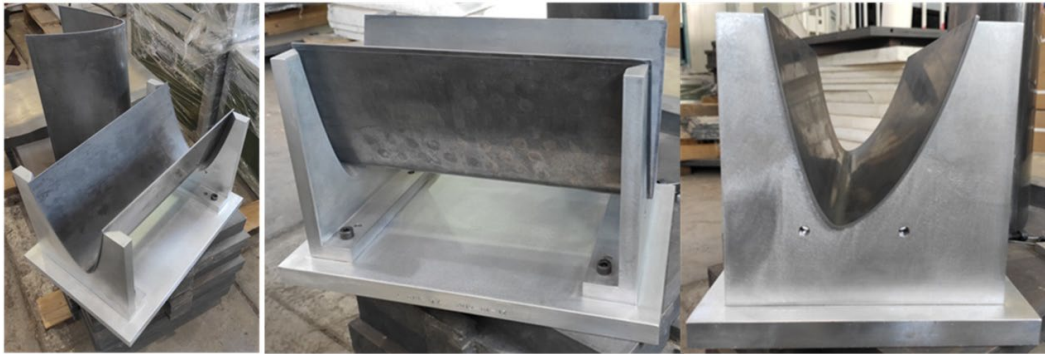


Fig. 8. Successfully formed V-shaped part in different views

### Accuracy evaluation

The dimensional accuracy of the thermal forming V-shaped parts is measured. The tangent measure tooling was manufactured. The dimensional accuracy will be evaluated using the feeler gauge, as shown in Fig. 9. The clearance between the parts and the measuring tool is recorded at different positions of the side A and side B, as shown in Fig. 9. The measurement results of the dimensional accuracy of the two hot forming parts are shown in Table 1. The maximum clearance occurs at the position where the curvature of the part is large, which is 0.2 mm.

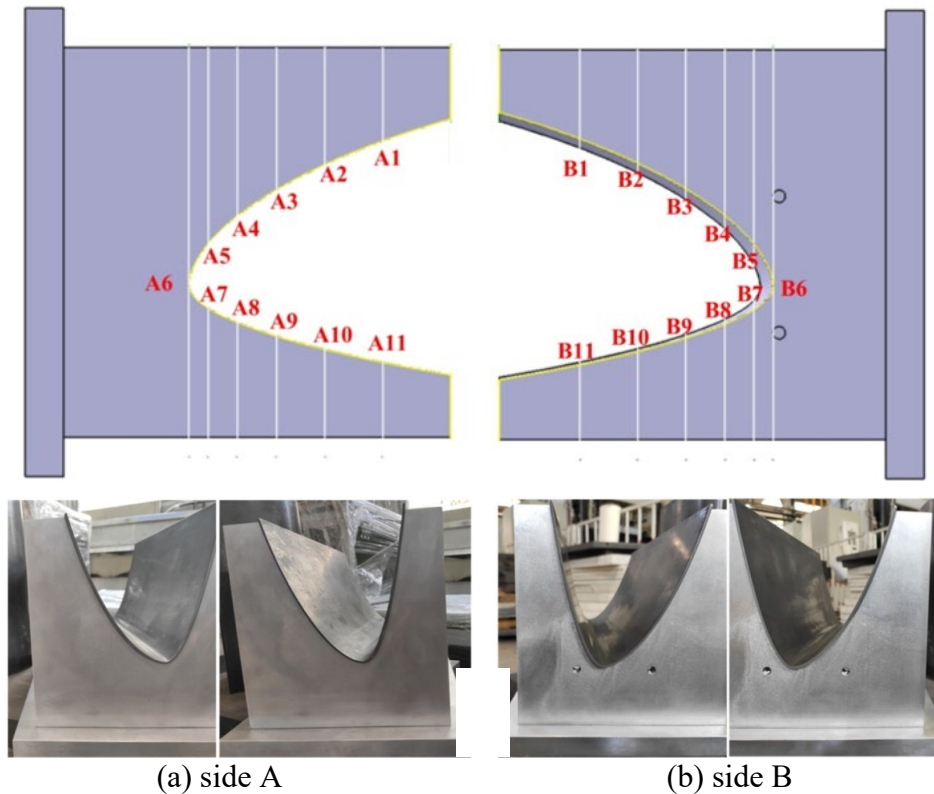


Fig. 9. Measuring position between measuring tool and V-shaped skin part in side A and B

Table 1 Measured clearance between measuring tool and V-shaped skin part

Position	Part1	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Clearance[mm]	Part1	0.1	0.15	0.1	0.15	0.2	0.15	0.2	0.15	0.1	0.1	0.1
Position	Part1	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
Clearance[mm]	Part1	0.1	0.1	0.1	0.15	0.2	0.15	0.2	0.1	0.1	0.1	0.1
Position	Part2	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Clearance[mm]	Part2	0.1	0.1	0.1	0.15	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Position	Part2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
Clearance[mm]	Part2	0.1	0.1	0.1	0.15	0.2	0.2	0.2	0.15	0.1	0.1	0.1

### Mechanical properties

The mechanical properties of the parts after thermal forming were tested. Temperature selected at room temperature, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C. After two thermal forming procedures, the yield stress and tensile strength are 324.65 MPa and 457.32 MPa respectively at room temperature. Mechanical properties of the composite are still in a desired high level after thermal forming. The energy spectrum analysis results of the detection sides are shown in Fig. 10, where red represents carbon element and green represents aluminum alloy matrix. It can be known that the FSP realizes the dispersion of carbon nanotubes in the aluminum matrix and the distribution is uniform.

Table 2 Mechanical properties of the formed part

Specimen	Temperature [°C]	Tensile speed [mm/min]	Yield stress [Mpa]	Tensile strength [Mpa]	Elongation [%]
1	RT	1	324.65	457.32	6.35
2	300	0.12	109.85	120.28	7.85
3		1.2	88.89	92.59	17.70
4		0.12	59.94	62.84	3.50
5	350	1.2	61.40	63.49	6.85
6		0.12	25.27	50.70	3.05
7		1.2	50.33	52.75	5.80
8	450	0.12	26.49	30.59	3.55
9		1.2	16.08	22.76	4.85
10		0.12	11.31	15.77	5.75
11	500	1.2	14.75	16.87	6.70

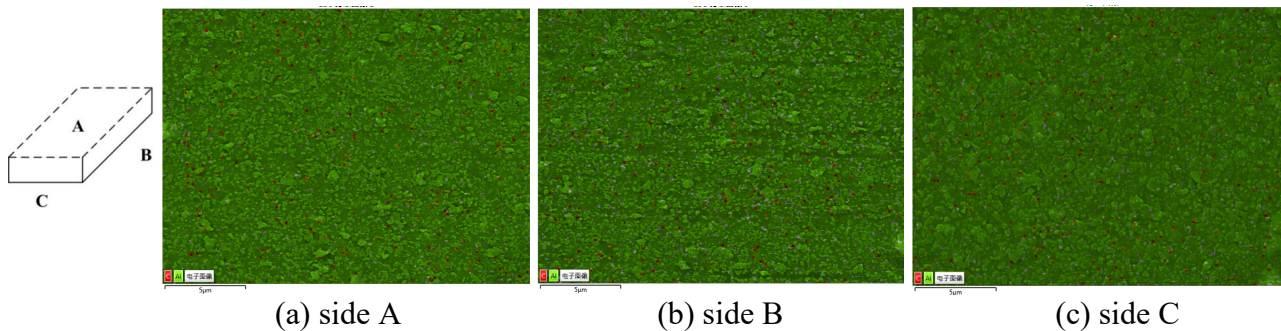


Fig. 10. Energy spectrum analysis images of the specimen cut from the formed part

### Conclusion

(1) CNT/2009Al sheet with 2 mm thickness was hot rolled. FSP was applied to improve the reinforcement uniform. The energy spectrum analysis images of the specimen cut from the formed part show that FSP realizes the dispersion of carbon nanotubes and the distribution is uniform.

(2) The thermal forming parameters of V-shaped skin part was optimized. The process was divided into two passes, and the forming temperature was 500 °C. The bottom radius of tooling in the first pass should not be less than  $R = 30$  mm. Mechanical properties of formed part are still in a desired high level after thermal forming. The V-shaped skin part of CNT/2009Al sheet was successfully formed, and the accuracy error was less than 0.2 mm.

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