



Special Feature: Innovative Technologies for the Automotive Structure and Processing

Research Report

Development of Moldless Casting Technique for the Fabrication of Aluminum Alloy Frame Components

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Report received on Sep. 26, 2019

■ABSTRACT■ Moldless casting, which is often referred to as capillary shaping, is an upward pulling directional solidification technique to fabricate a product directly from aluminum alloy melt. Aluminum frame components with inner ribs, variable cross-sections and bent geometries can be fabricated by this technique. High production flexibility is also an advantage of this approach. This article describes moldless casting with reference to equipment, a scientific basis to improve the thickness accuracy of a product and the forming rate, and the mechanical properties and microstructure of 6000 series aluminum alloy. Two automotive applications are also addressed. The first is a crash box with a wavy geometry designed to increase absorption energy. The moldless casting technique was applied to form the wavy shape. The absorption energy for the wavy type crash box determined by a drop-weight test was higher than that for a conventional crash box. The second is an aluminum frame with inner ribs and two bent sections. This frame was heat treated under T6 conditions, i.e. solution treatment at 805 K for three hours and artificial aging at 444 K for eight hours, and some other parts were welded onto the frame surface. The components were assembled as rear members of a concept car known as “KIKAI” exhibited in 2015.

■KEYWORDS■ Capillary Shaping, Design Freedom, On-demand Manufacturing, Flexible Production

1. Introduction

The automotive industry faces significant challenges with respect to the sustainable development of mobility. The development of light-weight vehicles is one of the most important aspects to decrease the impact of vehicles on the environment. For decades, attempts have been made to reduce the weight of car body structures, which include weight reduction of powertrains and batteries. However, it is desirable to develop new manufacturing techniques that enable optimization of vehicle structures to further reduce the weight of the vehicle body.

Moldless casting⁽¹⁻¹³⁾ is an upward pulling directional solidification technique that can be used to fabricate hollow aluminum alloy products with inner ribs and bent sections. Directional solidification prevents the formation of solidification shrinkage porosity and hot tearing of wrought alloys, e.g., 6000 series alloys. Aluminum alloy frames with excellent mechanical properties can be obtained using this technique. Moldless casting is also suitable for on-demand manufacturing and shortening of the lead time. This

technique requires a shaping device to define the cross-section of products and form path data for the definition of longitudinal dimensions. The shaping device can be prepared by additive manufacturing or numerical control machining systems. The forming path can be generated from a 3D-CAD model of products that can be easily modified by adjustment of the digital data. Thus, moldless casting offers flexible production.

This article describes the mechanism and facilities of moldless casting that involves a technical and theoretical approach to increase the formation rate and size precision. We also present the mechanical properties of 6000 series aluminum alloy specimens and two examples of automotive applications enabled through the application of this technique.

2. Moldless Casting

Figure 1 shows a schematic illustration of the moldless casting technique. An aluminum alloy melt is contained in a crucible and a shaping device is placed on the melt surface. The melt is withdrawn through

openings in the shaping device using a starting device to form a melt column above the melt surface. The starting device is then moved continuously upward with cooling of the position higher than the melt column, so that the top of the melt column is directionally solidified.

Figure 2 shows a schematic illustration of an apparatus for the fabrication of a product. Straight and bent product sections are fabricated by vertical pulling and rotary pulling. Combinations of vertical pulling and horizontal movement of the shaping device are alternative options used to fabricate a bent section with a large radius or an inclined section. Coolant air is blown from both the outer and inner sides of the melt column to achieve faster pulling. Coolant air for internal cooling is typically supplied through a melt-immersed pipe for easier pulling operation, although the internal cooling efficiency is reduced due to elevation of the coolant air temperature.⁽¹¹⁾ A laser positioning system is used to adjust the pulling rate and falling melt level associated with melt consumption.

The cross-sectional geometry of the product is determined not by the shaping device but by the melt column shape. Therefore, control of the thermal conditions is important for obtaining products with a precise wall thickness.^(7,10) However, the thermal conditions during the pulling process are varied depending on many parameters, such as the change in the cross-sectional dimensions, difference in the pulling rate at the outer and inner positions during rotary pulling, melt temperature fluctuation, and the unevenness of the cooling systems. High thickness

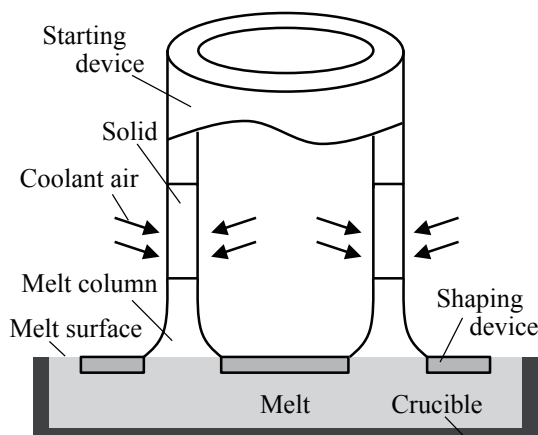


Fig. 1 Schematic illustration of moldless casting of hollow product.

accuracy can be achieved when the melt temperature, pulling rate and cooling conditions are maintained within a thermally stable range ($b \approx B$), where b is the product thickness and B is the opening width of the shaping device.^(7,10)

Figure 3 shows examples of A6063 aluminum alloy specimens fabricated by this technique. The maintenance of thermally stable conditions allowed the production of straight pipes with wall thicknesses of 2.6 ± 0.1 mm and 6.3 ± 0.3 mm (Figs. 3(a) and (b)). Hollow specimens with an inner rib (Fig. 3(c)) were fabricated using two inner cooling nozzles. The cross-sectional geometry can be changed by the use of variable shaping devices (Figs. 3(d) and (e)). A bent pipe (Fig. 3(f)) was fabricated by rotary pulling, whereas an inclined geometry (Fig. 3(g)) was fabricated by the combination of vertical pulling and horizontal movement.

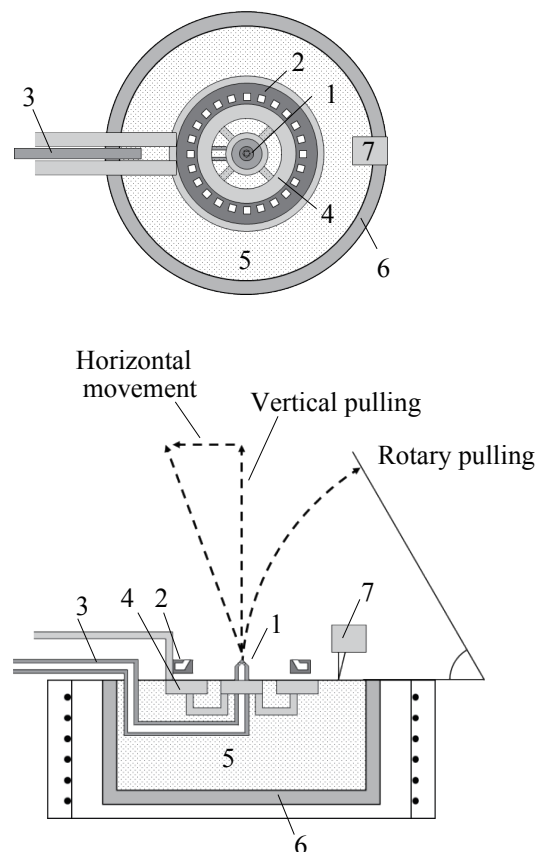


Fig. 2 Schematic illustration of the apparatus, inner cooling nozzle (1), outer cooling nozzles (2), melt-immersed pipe (3), shaping device (4), melt (5), crucible (6), laser positioning system (7).

3. Maximum Pulling Rate

A theoretical analysis was conducted to determine the maximum pulling rate during moldless casting under optimal cooling conditions.⁽¹³⁾ For a pure aluminum specimen with a 3-mm-thick wall, the maximum pulling rate was approximately 2.2 mm/s when the coolant air temperature was 323 K, the heat transfer coefficient between the coolant air and specimen was $460 \text{ W/m}^2\cdot\text{K}$ (strong air blowing), and the melt temperature was 993 K (no superheating).

However, the actual pulling rate is much lower than the theoretical maximum value. One of the most important factors for increasing the pulling rate is to improve the internal cooling efficiency. As the flow rate of the coolant air increases, the coolant air temperature decreases and the heat transfer coefficient between the coolant air and the product increases. However, high air velocity at the outlet of the inner cooling nozzles induces pressure drops inside a hollow product due to fluid dynamic effects, which leads to the collapse of the melt column. Control of the internal air pressure

during the pulling of hollow products is a useful way to avoid this problem. This technique has been used to increase the pulling rate up to 1.8 mm/s in the case of an A6063 aluminum alloy pipe with a 3-mm-thick wall.⁽¹³⁾

4. Microstructure and Mechanical Properties

Figure 4 shows the microstructure of A6063 aluminum alloy observed in pipes with and without Ti addition (hereafter referred as A6063 and A6063-Ti), where the A1 axis is in the wall thickness direction, the A2 axis is in the width direction, and the A3 axis is antiparallel to the pulling direction. The chemical composition of the alloys is listed in **Table 1**. In the case of A6063 alloy, a columnar structure was formed. Dendrites in this structure were aligned antiparallel

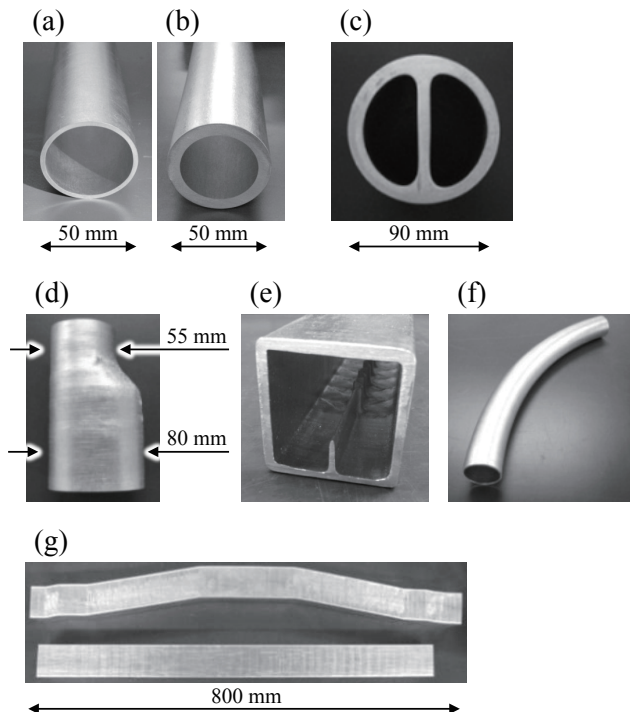


Fig. 3 Examples of A6063 aluminum alloy specimens. (a), (b) Straight pipes, (c) straight pipe with an inner rib, (d) pipe with variable cross-section, (e) square pipe with a wavy inner rib, (f) bent pipe, (g) square pipe with inclined section.

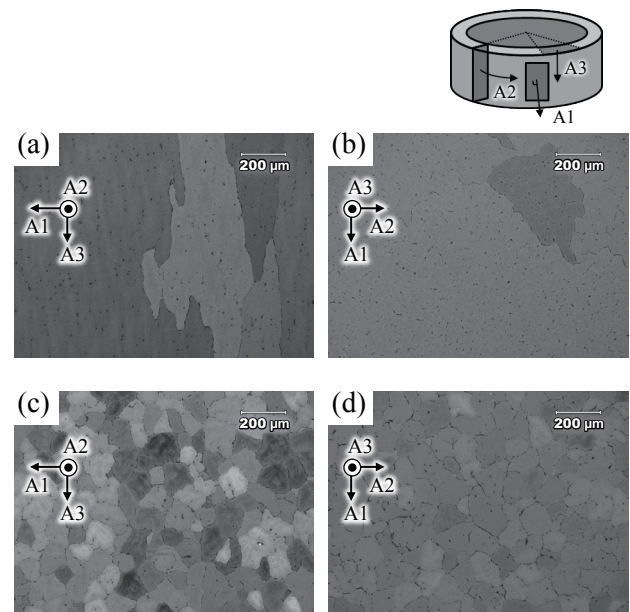


Fig. 4 Microstructures of (a), (b) A6063 alloy and (c), (d) A6063-Ti alloy.

Table 1 Chemical composition. (mass %)

Alloys	Cu	Si	Mg	Fe	Ti	Al
A6063	0.01	0.58	0.74	0.08	0	bal.
A6063-Ti	0.01	0.56	0.74	0.08	0.06	bal.

to the pulling direction because the melt solidified directionally at the top of the melt column. The dendrite growth axis is in the [001] direction, which is coincident with the preferred growth axis of aluminum. In contrast, equiaxed grains were randomly distributed in the solidified structure of the A6063-Ti alloy.

Figure 5 shows the relationship between the fracture strain, ϵ_f , and the ultimate tensile strength, σ_{UTS} , of A6005C aluminum alloys with columnar and equiaxed grain structures after T6 heat treatment, i.e., solution treatment at 805 K for three hours and artificial aging at 444 K for eight hours.⁽¹²⁾ The fracture strain and the ultimate strength of the equiaxed structure specimens were more than 10% and 270 MPa, respectively, which were as high as those for the wrought specimens. In the case of the columnar structure, the ultimate tensile strength parallel to the pulling direction (referred to as 0°) was higher than that perpendicular to the pulling direction (referred to as 90°). This anisotropy was also quite low in the case of the equiaxed structure.

5. Applications

5.1 Crash Box

A crash box is an energy absorption component placed in front of side members to protect a vehicle from serious damage during an accident. The crash box also plays an important role in increasing driver and passenger safety. A high energy absorption efficiency is required to minimize the crash box size. As shown

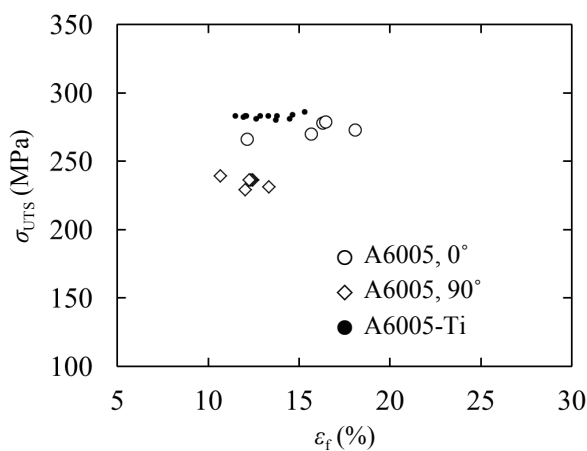


Fig. 5 Relationship between fracture strain ϵ_f and ultimate tensile strength σ_{UTS} of A6005C and A6005C-Ti alloys after T6 heat treatment.

in **Fig. 6**, the absorption energy is determined by integrating the deformation force, F , over the deformation length, L . The vehicle design limits the deformation length (crash box size) and the initial peak deformation force is designed based on safety requirements. Therefore, the maximum absorbed energy is ideally given by the area enclosed by the solid line. However, in practice, the crash energy is absorbed by the buckling deformation of the crash box, and the deformation force fluctuates depending on the number of buckling deformations, as indicated by the broken line. Thus, the real absorption energy is lower than the ideal maximum value. One possible design to decrease the absorption energy loss due to the fluctuation of the deformation force is a wavy shape that increases the number of buckling deformations and offers a more stable deformation force.

Figure 7 shows illustrations of two types of crash

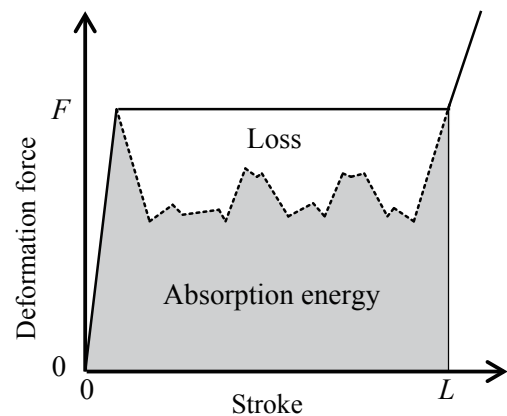


Fig. 6 Schematic illustration of absorption energy.

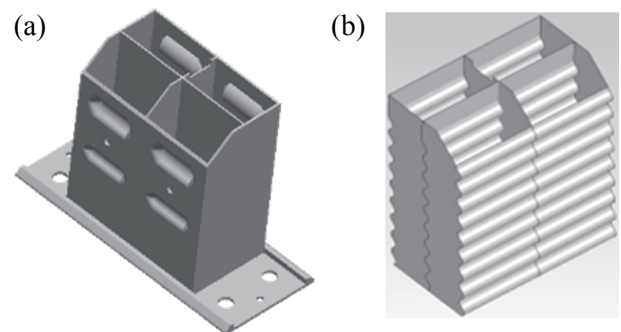


Fig. 7 Illustrations of crash box designs. (a) Conventional type, (b) wavy type.

boxes.⁽⁹⁾ The conventional crash box has inner ribs and is fabricated by an extrusion technique. Buckling deformation occurs at three regions in a conventional crash box. A wavy type crash box also has inner ribs and is designed to deform at the top and bottom of the wavy shapes. Extrusion is an inappropriate method to produce wavy type crash boxes; therefore, moldless casting was attempted to fabricate a crash box for which the combination of vertical pulling and horizontal movements was controlled.

Drop-weight tests were then conducted to measure the absorption energy for the conventional and wavy type crash boxes. **Figure 8** shows photographs of the wavy type crash box before and after the drop-weight test. In this case, the wavy type crash box showed a higher weight efficiency of approximately 25% in terms of the absorption energy than the conventional type crash box.⁽⁹⁾

5.2 Aluminum Frames

Trials were conducted to apply moldless casting to the fabrication of aluminum frames. **Figure 9(a)** shows an example of frame components with inner ribs and two bent sections.⁽⁹⁾ The total pulling length was approximately 1500 mm. The radii of the first and the second bent sections were approximately 200 mm and 2000 mm, respectively. The first bent section was formed by rotary pulling, whereas the second bent section was formed by a combination of vertical pulling and horizontal movement of the shaping device.

Figure 9(b) shows this frame component made of A6005C aluminum alloy.⁽⁹⁾ After heat treatment under T6 conditions, some other aluminum components were welded onto the surface of these frames. The components were then assembled as rear members of a concept car known as “KIKAI”, exhibited in 2015 (**Fig. 10**).

6. Summary

This article described the mechanism and facilities for moldless casting, including technical and theoretical approaches to increase the forming rate and size precision. High thickness accuracy can be achieved if the forming conditions are maintained within the thermally stable range. The forming rate can be increased to 1.8 mm/s for an A6063 aluminum alloy pipe with a 3-mm wall thickness by control

of the internal air pressure supplied through the melt-immersed type pipe. The mechanical properties of 6000 series aluminum alloy specimens produced by this technique were also described. Anisotropic properties were found in the case of the columnar structure specimen, while the anisotropy was quite low in the case of the equiaxed grain structure specimen.

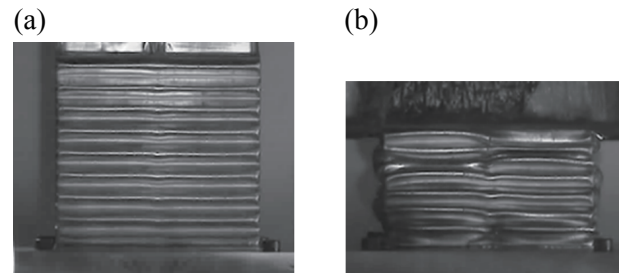


Fig. 8 Photographs of wavy type crash box, (a) before and (b) after drop-weight test.

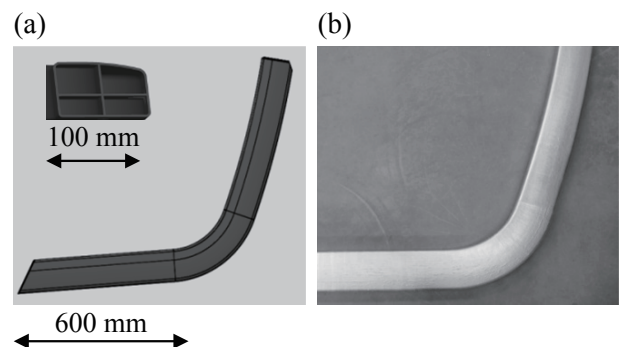


Fig. 9 (a) 3D-CAD model and (b) photograph of frame component with inner ribs and bent sections.



Rear side member

Fig. 10 Concept car “KIKAI”.

Hollow aluminum alloy products with inner ribs, variable cross-sections and bent geometries can be fabricated by the moldless casting technique. Automotive devices with superior properties were designed by taking advantage of these geometries. A wavy type crash box showed more weight efficiency for the absorption energy than a conventional crash box. Hollow frame components with inner ribs and bent sections were also used as rear members of a concept car. These results indicate that it is possible to reduce weight and increase the shape freedom of vehicles by application of this technique.

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