Acta Materialia 104 (2016) 180–189

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Thermal stability in fabricating hollow aluminum alloy products using the capillary shaping technique

Jun Yaokawa [a, *], Yasushi Iwata [a], Yoshio Sugiyama [a], Naoaki Sugiura [b], Yuichi Furukawa [b]

[a] *Toyota Central R&D Labs., Inc., Nagakute 480-1192, Japan*
[b] *Toyota Motor Corporation, Toyota 471-8571, Japan*

ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form
18 November 2015
Accepted 21 November 2015
Available online 13 December 2015

Keywords:
Aluminum alloys
Processing
Heat flow and solidification
Directional solidification
Solid/liquid interface

ABSTRACT

Capillary shaping (CS) is a directional solidification technique by which hollow aluminum products with inner ribs, a variable cross-section, and a bent geometry can be fabricated. Therefore, CS is an attractive option for the manufacture of aluminum automotive frames with the optimal design. However, several processing parameters affect the thickness accuracy of the products because the product geometry is not defined by molds but by the meniscus shape and heat balance at the solid–liquid interface. In this study, the thermal stability of the CS technique and the thickness accuracy of commercial grade pure aluminum and Al–Si binary eutectic alloy hollow products fabricated under non-uniform thermal conditions were investigated using temperature measurements, solidification structure analysis, and thermal analysis based on experimental, analytical and numerical approaches. High thickness accuracy was achieved when the pulling process was carried out under thermally stable conditions, under which the effects of the thermal non-uniformity were canceled out by those of a change in height of the solid–liquid interface. The thermal stability was maintained when the pulling rate was below a critical value. Finally, factors affecting the critical pulling rate are discussed and a heat transfer model for critical pulling rate analysis is proposed.

1. Introduction

Aluminum frames have been used in automobiles to improve ride comfort and reduce weight. Their hollow geometry with inner ribs offers a high structural stiffness. Aluminum extrusions are widely applied as frame components due to the high mechanical strength, elongation, reliability, and productivity. In recent years, more complicated shapes such as variable cross-sections and bent geometries are desired for aluminum frame components to reduce the weight of electric vehicles (EVs), hybrid vehicles (HVs), and fuel cell vehicles (FCVs). Furthermore, a requirement of design freedom of the frame components will increase for the autonomous vehicles. Although various manufacturing processes such as casting, forging, extrusion, rolling, and stamping have been utilized for the mass production of aluminum components, it is difficult to fabricate these newly designed aluminum frame components using conventional processes.

Capillary shaping (CS) is a solidification technique by which parts with a pre-determined shape are fabricated directly from the melt [1–19]. The Stepanov method [3,4] and the edge-defined film-fed growth method (EFG) [5–7] are the best-known CS techniques. CS techniques allow the manufacturing of the bent and/or twisting tubes with inner ribs [4,8], and have been applied for the fabrication of shaped crystals of sapphire [5,7], silicon [9,10], germanium [11], tin [12], copper alloy [13], iron alloy [14], nickel alloy [15], aluminum alloys [4,8,15–19] and salts [20]. Aluminum alloy products fabricated by CS techniques have shown high elongation and high strength due to the robust structure created by the directional solidification [8]. Moreover, the directional solidification of the CS techniques permits the shaping of alloys with high mechanical strength and elongation such as wrought aluminum alloys, despite their high hot-cracking sensitivity [21,22]. Therefore, CS is a novel manufacturing process that enables the fabrication of aluminum frame components with complex shapes. In the fabrication of automotive components using CS, however, the dimensional accuracy of the products is one of the most important concerns, because CS techniques do not use molds to define the product shape, so several processing parameters can affect the dimensional accuracy.

---

* Corresponding author.
E-mail address: e1454@mosk.tytlabs.co.jp (J. Yaokawa).

http://dx.doi.org/10.1016/j.actamat.2015.11.038
1359-6454/

In CS, a melt column is initially formed above the melt surface using a pulling device (Fig. 1). The top of the melt column is the solid–liquid (S/L) interface. The cross-section of the melt column is controlled by shaping devices placed below the S/L interface. The pulling device is continuously withdrawn upward, cooling the position slightly above the S/L interface so that continuous solidification takes place. The longitudinal geometry of the product is defined by the pulling path, whereas the cross-sectional geometry is varied by the movements of the shaping devices. It must be noted that the final dimensions of the products are determined not by the shaping devices but by the meniscus shape of the melt column, since the S/L interface is located away from the shaping devices. Thus, a high dimensional accuracy can be achieved if the desirable meniscus shape is maintained. Therefore, the pulling process must be conducted under meniscus stable conditions. According to the previous studies, the meniscus stability is maintained when $b > B/2$, where b is the thickness of the top of the melt column (thickness of the product) and B is the thickness of the bottom of the melt column [8,23–26]. The thermal conditions and the solidification rate also affect the thickness of the products because heat balance must be satisfied at the S/L interface [8]. In CS, the solidification rate is almost the same as the pulling rate. Therefore, the thickness of the products is defined not only by the meniscus shape but also by the heat balance associated with the thermal conditions and the pulling rate [8,16–18].

According to these studies, it is important to maintain the proper thermal conditions required by the heat balance in order to fabricate products with high thickness accuracy. Thus, the steady-state temperature field in CS has been investigated for the forced convection cooling of aluminum alloys [8,19]. However, the thermal conditions during the pulling process are often unsteady and non-uniform during the fabrication of frame components with bent geometries, because 1) the pulling rates are different at inner and outer positions during pulling with rotation, 2) the cross-sectional dimensions and thickness of the products vary as the pulling process progresses, and 3) fluctuations of the melt temperature occur due to natural convection. Furthermore, there is some thermal non-uniformity in the manufacturing equipment in general, including cooling systems for the solid region and the melt heating system. In these cases, high thickness accuracy can be achieved if the pulling process is conducted under thermally self-stabilizing conditions. Therefore, it is necessary to investigate the thickness accuracy with consideration of the thermal stability.

The CS is a technique which will meet a requirement of a cost reduction since CS equipment is simple, clean, inexpensive and easy to automate [8], although the pulling rate of CS is so slow. In fabricating automotive components with high thickness accuracy, however, the pulling process must be operated within the thermal stability and at a pulling rate as high as possible because the pulling rate of CS is so slow and directly affects the productivity. Although analysis of the pulling rate has been required, there have been few investigations of the pulling rate that took the thermally self-stabilizing conditions into account.

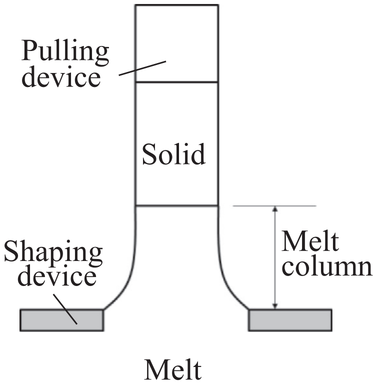

Fig. 1. A schematic drawing of the capillary shaping.

This paper focuses on thickness accuracy and thermal stability in the fabrication of hollow aluminum alloy products using CS under non-uniform thermal conditions. We investigated the temperature distribution, the meniscus height, the growth direction of the solidification structure, and the thicknesses of pure aluminum and Al–Si eutectic alloy cylindrical specimens. Pure aluminum and the Al–Si eutectic alloy were used because their constant melting points made it easy to determine the meniscus height from the temperature distribution. The results demonstrated that aluminum pipes could be fabricated with acceptable thickness accuracy using CS under non-uniform thermal conditions. High thickness accuracy was achieved only when the pulling process was conducted under thermally stable conditions. Processing parameters that affected the thermal uniformity were evaluated on the basis of the experimental results combined with analytical and numerical models based on the heat transfer. We also propose a model for analyzing the pulling rate in CS.

2. Methods

2.1. Experimental procedure

Fig. 2 shows two illustrations of the apparatus. Melts of 99.8 wt% purity aluminum (henceforth referred to as 99.8Al) and the Al–12Si alloy (hereafter the units are wt%) listed in Table 1 were held in an

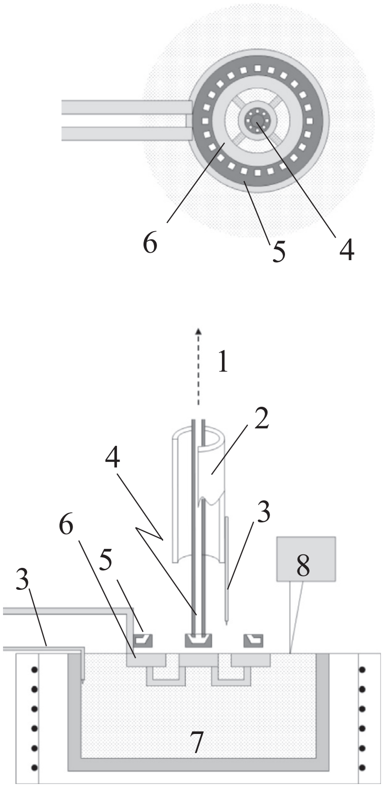

Fig. 2. Schematics of the apparatus. 1) pulling path, 2) starting device, 3) thermocouples, 4) inner cooling nozzle, 5) outer cooling nozzle, 6) shaping device, 7) melt, 8) laser distance sensor.