Journal of Materials Processing Technology 182 (2007) 220–228

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

A study on quantitative formability assessment of rheological materials based on the microstructural characterization with a moderate control of the process

Hong-Kyu Jung [a], Han-Goo Kim [b], Chung-Gil Kang [b,*]

[a] National Research Laboratory for Thixo-Rheo Forming (NRL/TRF), School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea

[b] School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea

Received 28 April 2005; received in revised form 20 July 2006; accepted 31 July 2006

Abstract

The semisolid forming (cleaner rheological forming) of aluminum alloys is a new net shape manufacturing method that incorporates elements of both forging and casting. It is characterized by the use of induction heating to reheat billets to the highest possible solid fraction in order to maximize the mechanical properties such as strength, wear resistance and elongation. It is necessary to develop tailored alloys specifically for cleaner rheological forming (CRF). The selection is basically from the entire range of cast and wrought aluminum alloys, although most of these alloys were optimized either for the casting or for the forging process. Nowadays, their formability evaluation in the semisolid state has rarely been investigated, and more essentially, it lacks a systematic theoretical base for dealing with unexpected behavior under the new and possibly extreme conditions encountered as we expand the limits of this criterion. So, the present article uniquely focused on an advanced description (advanced JK criteria) to evaluate the formability and castability of next-generation nonferrous materials such as cast and wrought aluminum alloys in the semisolid state based on the microstructural characteristics with an appropriate control of the process. Using the proposed criteria (advanced JK criteria) to evaluate the quantitative formability of cleaner rheological materials in the semisolid state shows that a nine-point alloy represents an optimal semisolid formability while a zero-point alloy is extremely unsuitable for CRF, confirming the validity of the proposed criteria.

Keywords: Advanced JK criteria; Cleaner rheological materials; Microstructural characterization; Moderate control of process; Quantitative formability assessment

1. Introduction

The semisolid forming (cleaner rheological forming) of high quality products using lightweight materials such as aluminum and magnesium alloys has reached the status of an accepted industrial process. Especially, various semisolid formed components such as air compressor parts, suspension components, engine brackets, and hydraulic products are now being provided to the automotive industry [1–11].

This technology was discovered during research on hot tearing undertaken at the Massachusetts Institute of Technology (MIT) in the early 1970s. To investigate the magnitude of the forces involved in deforming and fragmenting dendritic growth structures, MIT scientists constructed a high-temperature viscometer. They poured molten Pb–Sn alloys into the annular space created by two concentric cylinders and measured the forces transmitted through the freezing alloy when the outer cylinder was rotated. Through these experiments, it was discovered that when the outer cylinder was continuously rotated, the semisolid material showed remarkably low shear strength even at relatively high solid fractions. This property was attributed to nondendritic spheroidal microstructures.

The production of semisolid raw material (or starting material) with an equiaxed microstructure has been brought to full commercialization, and the use of semisolid formed products is broadening in the automotive, aerospace, military, and other industrial fields.

* Corresponding author. Tel.: +82 51 510 2335; fax: +82 51 512 1722.
E-mail address: cgkang@pusan.ac.kr (C.-G. Kang).

0924-0136/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2006.07.036

Nomenclature

A	area of the primary α structures (μm^2)
fs	solid fraction (%)
P	perimeter of the primary α structures (μm)
S_f	shape factor (dimensionless)

The advantages of cleaner rheological forming (CRF) using the lightweight nonferrous materials like next-generation magnesium and aluminum alloys have enabled it to compete with many conventional metal forming processes in a number of different applications. Rheologically formed components have replaced die castings, permanent mold and investment castings, impact extrusions, and conventional hot and cold forgings [1–18].

In a study of the CRF process, Fehlbier et al. [19] suggested the new methods for the characterization of the mold filling behavior of semisolid A356 alloy. Giordano et al. [20] proposed the semisolid forming technology regarding the development and production of three connecting rods with the alloy A356-T5, for the new automobile Renault Avantime. Jung and coworkers [2–4] suggested that to reduce the occurring possibility of defects, the liquid segregation be controlled as the multistage variation of the pressing velocity during cleaner rheological forming (CRF).

Nowadays, there is a lack of a systematic theoretical base for dealing with unexpected behavior under the new and possibly extreme conditions and for evaluating the formability of next-generation nonferrous materials in the semisolid state. Any single alloy or alloy group cannot satisfy these requirements simultaneously. It is, thus, necessary to select a tailored alloy for the specific application. The selection is basically from the entire range of cast and wrought aluminum alloys, although most of these alloys were optimized either for the casting or for the forging process.

Therefore, in this present study, advanced criteria based on the microstructural characterization with an adaptive control of the process are proposed to assess the quantitative formability of cleaner rheological materials in the semisolid state. The suggested criteria are concentrated on the concept of hybrid elements of both solid and liquid and treat the reheated billet (solid fraction, primary α-phase and eutectic microstructure) to the mushy state.

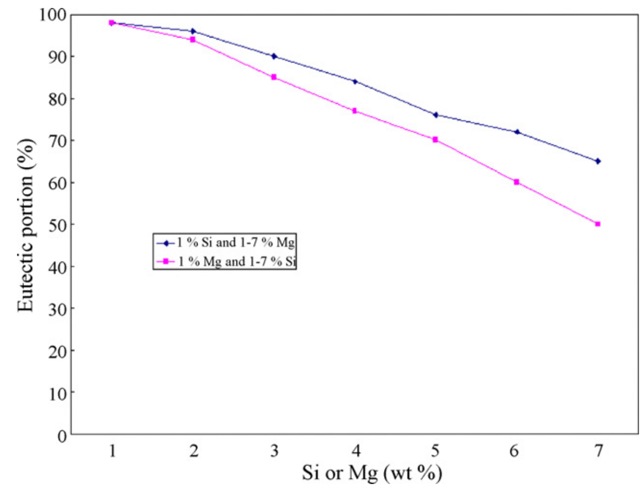

Fig. 2. Equivalent solid fraction and eutectic portion for the ternary system Al–Si–Mg involving up to 7% Si and 7% Mg, respectively. This eutectic portion increases with silicon content in a nearly linear relationship, reaching approximately 50% at 7% Si.

2. Criterion items for quantitative formability evaluation of cleaner nonferrous rheological materials

2.1. Phase diagram for Al–Si binary and Al–Si–Mg ternary alloy systems

A criterion for evaluating the quantitative formability of an alloy in the semisolid state is evident directly from the phase diagram (Fig. 1). Pure metal and eutectic alloys (Case II) are not semisolid formable because of a lack of solidification interval. At the semisolid forming stage, furthermore, the material must consist of a solid globular phase surrounded by melt. This melt may be composed of a liquid eutectic alone (Case I). In the case of alloys with a sufficient solid-phase solubility of the alloying elements (Case III), the liquid phase may be enriched with alloying elements as a result of selective microsegregation control.

Case I includes hypoeutectic alloys such as A356 and A357. Due to 7% silicon content these materials are about 40% eutectic, so that even if the eutectic is melted completely their liquid phase portion will reach the equivalent volume fraction. On the other hand, the maximum selectable solid fraction is 60%, because the eutectic must be melted completely to ensure better mechanical

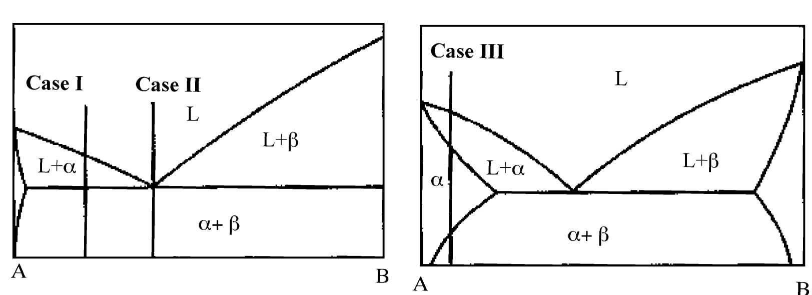

Fig. 1. Schematic illustration for phase diagrams of binary alloy system. A simple criterion for evaluating the formability of next-generation cleaner rheological materials (CRM) is obvious directly from these phase diagrams.