Journal of Materials Processing Technology 212 (2012) 171–180

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

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

Through-process sensitivity analysis on the effect of process variables on strength in extruded Al–Mg–Si alloys

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ARTICLE INFO

Article history:
Received 1 February 2011
Received in revised form 14 July 2011
Accepted 31 August 2011
Available online 6 September 2011

Keywords:
Aluminium
6060
Through process
Modelling
Sensitivity analysis

ABSTRACT

A concept of through-process modelling for studying the effect of process variables on the strength of extruded Al–Mg–Si alloys is presented. Five models are integrated to model casting, homogenisation, extrusion and ageing of the alloys. It is demonstrated that through-process modelling can be utilised to study isolated effects from variations in processing parameters along the value chain on the strength in the end product, which is usually difficult to obtain from experiments. In the present work it has been focused on strength after artificial ageing and the most critical parameters to follow were therefore the Mg and Si and whether these elements appear in solid solution or present in constituent phases. The as-cast and homogenised structures were predicted reasonably well by the models, and it was found that the casting parameters have a significant influence on the density of constituent particles. Chemical composition and cooling rate from extrusion temperature are the variables with the most prominent effect on the yield stress of extruded and aged sections.

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1. Introduction

Consistent control of mechanical properties is crucial for all kinds of extruded aluminium products, including sections for the building industry, profiles for structural applications in the automotive industry and tubes for the heat transfer segment. Extruded aluminium sections are generally sold with a specific strength required by the customer, which varies quite significantly depending on the application. Usually, the claim from customers is a minimum strength-limit, which is met by the producers by aiming for strength well above this limit to account for the strength variations caused by the production processes. Recently, customers have started to require a maximum strength-limit in addition to the minimum limit. The required strength-limit-window can often be quite narrow, and it has therefore become crucial for extruders to be able to reduce the strength variability in the extruded sections.

Reducing variations from production processes is not a simple task, and the complexity increases with increasing numbers of process steps and process parameters. A reasonable approach to the task is to identify the process parameters with the most significant impact on the variability, and make actions on these. One way to identify these parameters is to do a sensitivity analysis on measured data obtained from production. However, the available data might not cover every parameter, making it insufficient for pinpointing the governing factors. Implementing new parameters into the production database is generally expensive, as is dedicated experiments in the plant. Computer modelling and simulation offer an alternative to real life data, and is a cheaper and less time consuming way to solve the task.

The objective of the present paper is to show the potential of applying through-process modelling as a tool for analysing the sensitivity of various process parameters on the final strength in extruded Al–Mg–Si alloys (AA6xxx series alloys), which is used in the majority of extruded aluminium sections. The task of modelling the strength of extruded AA6xxx sections is basically to keep track of the Mg and Si in solid solution through the process stages, and to predict the amount of the strength-enhancing β''-Mg_5Si_6 phase, described by Andersen et al. (1998), precipitated during the final age hardening stage. This is accomplished by combining existing available models, developed for each process stage, into a through-process modelling scheme. This scheme is used in a sensitivity analysis on the effect of process parameters on the yield stress of extruded and aged sections.

Similar through-process modelling approaches have recently been reported by Engler et al. (2007) and Furu et al. (2004). These approaches combined microchemistry models, appropriate

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doi:10.1016/j.jmatprotec.2011.08.020

microstructure models for deformation and recrystallisation and finite element models (FEMs). The latter were used to provide the thermomechanical history along the process chain, from casting to semi-finished product, which served as input for the microchemistry and microstructure models. In this way they were able to describe the microstructure and texture evolution during a number of process steps from casting to semi-finished products, e.g. rolled sheet and extruded profiles. The present work makes use of similar types of models, however, it is focused mainly on the microchemistry changes themselves and the final strength after ageing, while those former works focused on microstructure and texture and their relations to properties.

2. Production of extruded aluminium section

2.1. Thermal history

Aluminium in extruded sections has undergone large variations in temperature on its way from melt to finished product. A typical thermal history of Al–Mg–Si alloys is illustrated in Fig. 1, where also estimated levels of Mg and Si in solid solution are included. The aluminium extrusion billet is first cast by Direct Chill casting with a casting temperature of about 700 °C. In the second process stage, homogenisation of the billet microstructure is conducted by heating the billet to approximately 580 °C and keeping at this temperature for several hours, followed by cooling down to room temperature at a specified minimum cooling rate. During the third stage, extrusion, the metal is pre-heated to temperatures between 440 °C and 500 °C, loaded into the extrusion chamber, and extruded through a die. Due to high reduction ratios and high extrusion speeds the extrusion process generates heat in the metal, leading to temperatures in the extruded profiles up to 600 °C. When the metal has passed through the die, it is cooled to room temperature at specified cooling rates depending on the requirements of the end products. In the final stage, the extruded sections are aged at temperatures typically in the range 150–200 °C for several hours to precipitate coherent strengthening Mg–Si phases. Different Mg and Si containing constituent particles, whose stability is temperature dependent, can form in Al–Mg–Si alloys during different thermomechanical processing steps, which will influence the amount of Mg and Si elements available in the solid solution for precipitation of the strengthening precipitates during age hardening treatment. Therefore, it is inevitable that variations in this temperature–time cycle will affect the strength of the extruded profile both in as-extruded condition and after the ageing process.

2.2. Age hardening of Al–Mg–Si alloys

The strength in aluminium extrusions depends on the chemistry of the given alloy and the processing conditions for the product from the casting process and through the whole processing chain to the ageing process. Both chemistry and processing conditions will influence the microstructure of aluminium alloys, including constituent particles, dispersoids, amounts of elements in solid solution, age-hardening precipitates, grain size, and texture. The main strength provider in Al–Mg–Si alloys is the coherent Mg–Si precipitates. The atomic structure of Mg–Si-precipitates depends on the age hardening cycle, in terms of temperature and time, and the amount of Mg and Si in solid solution in the aluminium matrix available to form the precipitates. In accordance with state-of-the art understanding of the precipitation behaviour in these alloys, Andersen et al. (2007) have described the precipitation sequence as:

$$\text{SSSS} \rightarrow \text{atomic clusters} \rightarrow \text{GP-zones} \rightarrow \beta'' \rightarrow \beta', \text{U1, U2, B}' \rightarrow \beta, \text{Si}$$

(SSSS, Super Saturated Solid Solution; β'', Mg_5Si_6; β', $Mg_{1.8}Si$; U1, $MgAl_2Si_2$; U2, MgAlSi; B′, $Mg_9Al_3Si_7$; β, Mg_2Si) where the β''-phase is the main contributor to strength. The SSSS-level of Mg and Si depends on the chemical composition of the alloy as well as the thermo-mechanical history of the material in the process stages prior to age hardening. This will influence how much Mg and Si is captured in constituent particles or other non age-hardening precipitates.

The solid solution level of Mg and Si before ageing depends primarily on the amount of non-hardening Mg and Si-containing precipitates in the material, in particular β'-$Mg_{1.8}Si$ rods (Andersen et al., 2005), which should be as low as possible to achieve high strength. In addition, the amount of Si tied up in constituent Fe-rich phases formed during solidification and homogenisation also influences the solid solution level of Si. The amount of Mg–Si precipitates depends on several processing parameters:

- *The homogenisation temperature and time*: Some Si is trapped in Fe-containing constituent phases like α-AlFeSi and β-AlFeSi, and in α-AlFeSi dispersoids formed during homogenisation, where the α-AlFeSi dispersoids act as nucleation sites for β'-$Mg_{1.8}Si$. The amount of Fe-containing constituent particles and the size, density and distribution of α-AlFeSi dispersoids are a function of alloy composition, homogenisation temperature and homogenisation time.
- *The cooling rate after homogenisation*: β'-$Mg_{1.8}Si$ in the extruded sections form in general during cooling from elevated temperatures. A low cooling rate favours the precipitation of the β'-phase, most of which will dissolve during preheating of the extrusion billet.
- *The preheating temperature and time during extrusion*: Reiso et al. (1996) found that coarse β'-particles may survive the preheating and extrusion process and thus reduce the solid solution level after extrusion. If the preheating is done at too low temperature and the time is too short, the β'-precipitates may not fully dissolve, and thus the age hardening potential is lowered.
- *The cooling rate after extrusion*: As with homogenisation, a low cooling rate after extrusion leads to increased amount of β'-particles.

As mentioned above, some of the Si will be tied up in the Fe-rich phases during the casting and homogenisation processes. Consequently, the temperature–time cycles of these up-stream processes will affect the Si-content available for precipitation of Mg–Si-precipitates in the final processing step of extrusions and thus have an important impact on the mechanical properties of the end product.

3. The modelling approach

There are five models involved in the present through-process modelling scheme. Four of the models are restricted to use within Hydro Aluminium, while the age hardening model is well accounted for in the literature, e.g. Deschamps et al. (1998) and Myhr and Grong (2000). The domain of each model is depicted in Fig. 1. The microstructure in as cast condition was simulated by coupling the models Alsim and Alstruc. In order to calculate phase transformations during the homogenisation process (heating, holding and cooling) which will affect the Si-content in Fe-phases, precipitation of Mg–Si particles and levels of solid solution, the Alstruc and Mg_2Si models were applied. The Mg_2Si model also covered extrusion, while the final model, *Premium*, was used to model age hardening. The models are described later.

All of the involved process stages except extrusion are basically temperature controlled, and the modelling of these processes

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