# Thermal Contraction of AA5182 and AA5083: Experiment and Simulation

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Keywords: Contraction, AA5182, AA5083, solidification, computer simulation, butt-curl, hot tearing

#### Abstract

Thermal contraction during and after solidification is an important phenomenon related to the origination of deformation and, therefore hot tearing and shape distortions during casting. The understanding of this phenomenon is crucial in design defect-free cast products and in numerical simulation of thermomechanical behaviour. This paper presents the results of experimental and numerical simulation work on the contraction during and after solidification of commercial AA5182 and AA5083 alloys. In the specially developed experimental set-up, the contraction is measured simultaneously with temperature while the material solidifies and cools down in the solid state. An elasto-viscoplastic constitutive model fitted to experimental data is used in finite element simulations of the contraction process. The results show that the contraction starts at a certain temperature in the non-equilibrium solidification, close to the non-equilibrium solidus, and that two tested alloys behave similarly. Good agreement is found between simulation and experimental results.

### 1. Introduction

During solidification, a metallic alloy passes through the solidification range that can be conditionally divided into two parts: semi-liquid (slurry) and semi-solid (mush) zones. Both are distinguished by the physical characteristics, i.e. material has good fluidity and no strength in the semi-liquid zone, while it has poor fluidity and some strength in the semi-solid region [1,2]. Enlargement of semi-liquid temperature range is very useful in reducing solidification defects such as hot cracking and porosity. In this case, good slurry fluidity will prevent the formation of solidification defects that are mostly caused by lack of feeding. Besides that, due to the narrowing of the semi-solid temperature range the accumulated contraction stress will be lower, which may reduce solidification cracking.

There are three terms usually used for characterizing shrinkage or contraction: solidification shrinkage, thermal contraction and linear contraction. The solidification shrinkage refers to volume shrinkage due to solidification phase transformation. The thermal contraction refers to volume contraction of the solid phase. The linear contraction refers to horizontal contraction during and after solidification [2].

During direct-chill (DC) casting, defects such as shape distortion (butt-curl, butt-swell, pullin), hot tearing, and porosity have been recognized. All of them are related to the shrinkage/contraction during solidification. A number of theories have been proposed to explain defect formation. Butt-curl is one of the shape distortion defects frequently occurring during the start-up of DC casting. This phenomenon involves bending upwards of the ends of the shell solidified against the bottom block. This bending is caused by excessive thermal stresses due to high cooling rates resulting from water impingement on the ingot surface. The occurrence of butt curl impairs the stability of the ingot on the starting block, and is therefore a potential safety hazard. Besides that, the partial loss of contact between the ingot and the bottom block temporarily reduces the heat transfer with possible shell re-melting and allows the intrusion of water between the ingot and the bottom block. In the worst case, the butt curl can graduate to ingot cracks.

Computer simulation is a recent issue for reducing or avoiding defect formation in relation to process parameters. The mechanism of deformation during and after solidification has to be understood in order to gain a comprehensive approach in modelling. One method to do that is to scale-down the billet for practical and economical reasons. By using a smaller sample, the experiment can be performed quickly. Besides that, validation of computer simulations can also be done relatively easy.

Experimental measurements of linear contraction during and after solidification of two Al–Mg–Mn alloys (AA5182 and AA5083) are reported in this paper. These experimental results are compared to the finite element (FEM) computer simulation of thermal contraction.

#### 2. Experiment

A contraction test apparatus is schematically shown in Figure 1. The set-up consists of an open mould with a special T-shaped cavity on one side and a movable wall on the other side, a water-cooled bronze base, a linear displacement sensor (LVDT) attached to the moving wall, a thermocouple for temperature measurement, and a personal computer for data acquisition. The dimensions of the mould gauge cavity are  $25 \times 25$  mm in cross-section and 100 mm in length, which is identical to dimensions used in earlier work [2] and is based on the original work of Novikov [3]. The experiment is described in more detail elsewhere [2]. The movement of the moving wall and the temperature in the centre of the sample at 1 mm from mould bottom are recorded simultaneously.



Figure 1: Schematic view of the mould and the sample used in experiments

Two aluminium alloys that have chemical compositions as shown in Table 1 are used. The materials are melted in a graphite crucible in an electrical furnace, the pouring temperature being 700 °C.

Table 1: Chemical composition of AA5182 and AA5083 alloys.

Γ	Alloy	Mg	Mn	Si	Fe	Cu	Zn	Ti	Cr
Γ	AA5182	3.60	0.16	0.21	0.26	<0.01	0.01	0.02	<0.01
Γ	AA5083	3.26	0.66	0.26	0.22	0.06	0.10	0.04	0.10

The linear contraction upon solidification is determined as follows [2]:

$$\varepsilon_s = \frac{l_s + \Delta l_{\exp} - l_f}{l_s} \times 100\% , \qquad (1)$$

where  $I_s$  is the initial length of the cavity,  $I_f$  is the length of the sample at the solidus temperature, and  $\Delta I_{exp}$  is the pre-shrinkage expansion.

The thermal contraction after solidification is determined according to the ASTM standard for thermal expansion coefficient [4]:

$$\alpha = \frac{(l_2 - l_1)/l_o}{T_2 - T_1} = \frac{1}{l_o} \frac{\Delta l}{\Delta T},$$
(2)

where  $I_o$  is the initial length of the sample at temperature  $T_o$ ,  $I_1$  and  $I_2$  are the lengths of the sample at temperatures  $T_1$  and  $T_2$ , respectively. Usually  $T_o$  is taken as a reference temperature, e.g. room temperature (20 °C).

#### 3. FEM Simulation

A fully three-dimensional model is used in this work. Due to the symmetry, only a half of the sample needs to be modelled. A coupled computation of stress and temperature field is applied for simulation, using 8-node brick elements with 8 Gauss integration points. The commercial FE package MSC.MARC is used for simulations.

All thermophysical properties applied in this simulation are taken from ref. [5] unless indicated otherwise. Some properties (thermal conductivity, specific heat, and Youngs' modulus) are implemented as functions of temperature, while the other properties are kept constant. The thermal contraction coefficient and the temperature of contraction onset are taken from our measurements.

Plastic deformation at subsolidus temperatures is described by a modified Ludwik model:

$$\sigma = K \left( \dot{\varepsilon}_p + \dot{\varepsilon}_{po} \right)^m \left( \varepsilon_p + \varepsilon_{po} \right)^n, \tag{3}$$

where  $\sigma$  is the true stress (MPa); *K* is the stress at a strain and strain rate of unity (MPa);  $\dot{\varepsilon}_p$  is the strain rate (s<sup>-1</sup>);  $\dot{\varepsilon}_{po}$  is a small constant plastic strain rate (10<sup>-4</sup> s<sup>-1</sup>);  $\varepsilon_p$  is the plastic strain;  $\varepsilon_{po}$  is a small constant plastic strain (10<sup>-2</sup>); *m* is the strain rate sensitivity coefficient; *n* is the strain hardening coefficient. The parameters *K*, *m* and *n* in this equation are fitted to the experimental data from ref. [6].

The following expression is used as the constitutive equation of the mush:

$$\sigma = \sigma_o \exp(\alpha f_s) \exp\left(\frac{mQ}{RT}\right) (\dot{\varepsilon})^m, \qquad (4)$$

where Q is the activation energy given by the solid phase deformation behaviour, *m* is the strain rate sensivity coefficient, *R* is the gas constant,  $\sigma_a$  and  $\alpha$  are the material constants

and  $\dot{\varepsilon}$  is the strain rate. The values for Q,  $\sigma_{o}$ ,  $\alpha$  and m are fitted to the experimental data [6].

The heat transfer between sample and mould is specified for two cases: contact and noncontact. The heat transfer coefficient in the contact situation is defined as a function of temperature, and in the non-contact situation as a function of gap distance.

#### 4. Results and Discussion

#### 4.1 Experimental Results

Figure 2 shows the grain structure of AA5182 and AA5083 alloys in the centre of the sample at a distance of 2 mm from the bottom. Both tested materials comprise equiaxed dendritic grains with an average grain size of 160  $\mu$ m for an AA5182 alloy and 210  $\mu$ m for an AA5083 alloy.





Figure. 2: Optical micrograph of grain structure in the centre of the sample at a distance of 2 mm from the bottom: a) AA5182 and b) AA5083.

Cooling curves at three different heights of the centre of the sample are shown in Figure 3. At temperatures higher than the solidus, these curves are clearly different, although the solidus temperature is reached at approximately the same time.

The vertical temperature gradient in the centre of the sample becomes very low below the solidus. That makes this technique suitable for measuring the thermal contraction coefficient at sub-solidus temperatures.



Figure 3: Measured temperature at 1 mm (1), 8 mm (2) and 15 mm (3) from the bottom of sample.

The measured contraction of AA5182 and AA5083 alloys is shown in Figures. 4 and 5. The obtained values are close for both alloys. First, an expansion is observed that is typical of aluminium alloys [2, 7]. This pre-shrinkage expansion is caused by gas evolution and pressure drop over the mushy zone [8]. At a temperature of 530 °C, the contraction is started. In the beginning, the contraction proceeds with acceleration on decreasing temperature. Later, the contraction occurs linearly till room temperature.

The accelerated contraction is primarily due to the combination of solidification shrinkage and thermal contraction of the solid shell. In this temperature range (500–530 °C) the thermal contraction coefficient is higher ( $26 \times 10^{-6} \text{ K}^{-1}$ ) than at sub-solidus temperatures (300–500 °C) when it becomes equal to  $24.6 \times 10^{-6} \text{ K}^{-1}$ .



Figure 5: Linear contraction of AA5083.

## Figure 4: Linear contraction of AA5182.

#### 4.1 Numerical Simulation Results

Calculated and experimental cooling curves agree well as shown in Figure 6. Computed temperature dependence of linear contraction correlates adequately to experimental results as can be seen in Figure 7. However, the simulations fail to reproduce the pre shrinkage expansion, which needs further insight in the expansion mechanism.



Figure 6: Measured (1) and calculated (2) temperature in the centre of sample.



Figure 7: Calculated (1) and measured (2,3) contraction of AA5182.

Distributions of temperature, contraction and strain at partially and fully solid samples are shown in Figures. 8 and 9, respectively. In Figure 8a, the temperature of the solid shell is around 513 °C (solidus temperature). The contraction gradient in the longitudinal (*x*) direction is not uniform due to the combination of solidification shrinkage and thermal contraction of the solid phase (Figure 8b). In Figure 9, the whole sample is solid (Figure 9a), and the contraction gradient is now uniform (Figure 9b) as the entire sample undergoes isotropic thermal contraction. The longitudinal strains show compression in all sections (Figures. 8c and 9c) because of the contraction.

The results of the simulation are in accordance with the experimental results – the contraction starts at a temperature above the solidus and the contraction coefficient changes at solidus temperature. The implementation of the thermal contraction phenomenon in the numerical simulation of solidification process is crucial in prediction of deformation related defects such as butt curl, pull-in, butt swell and hot cracking.



Figure 8: Calculated temperature (a), accumulated contraction in longitudinal direction with respect to the axes origin (b) and accumulated strain in longitudinal direction (c) after 20 sec.

Figure 9: Calculated temperature (a), accumulated contraction in longitudinal direction with respect to the axes origin (b) and accumulated strain in longitudinal direction (c) after 30 sec.

#### 5. Conclusion

From the experimental measurements and numerical simulations of thermal contraction of AA5182 and AA5083 alloys, it can be concluded that:

- 1. The thermal contraction behaviour of both alloys is similar.
- 2. The contraction starts at a certain temperature within the solidification range; is nonuniform above the solidus and uniform below the solidus.
- 3. Numerical simulations that take into account the temperature of contraction onset and the transition from semi-solid to solid contraction behaviour are in good agreement with the experimental data.

This research is part of the research program of the Netherlands Institute for Metals Research (www.nimr.nl) Project No. MP97014.

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