INTRODUCTION

In industry, grain refinement is a common way of achieving a proper, uniform, fine grain structure in wrought aluminum alloys, since metals and alloys usually solidify with a coarse, columnar grain structure under normal casting conditions.

Many theories exist to explain the mechanism of grain refinement [1, 2, 3]. Besides nucleant particles, like TiB$_2$ and TiC, found in commercial grain refiners, solutes also play an important role in grain refinement [4]. The extent of the grain-refinement effect of an individual solute can be expressed by the growth-restricting factor (GRF):

$$\text{GRF} = mC_o(k - 1)$$

where $m$ is the slope of the liquidus, $C_o$ is the concentration of the solute in the melt, and $k$ is the equilibrium partitioning coefficient [1]. In the presence of a number of elements in the alloy the GRF is taken as the summation of the individual elements, which means the interactions between solutes are neglected.

It is known that the GRF is inversely proportional to the growth rate of the grains [5, 6]. When the GRF is large, the rate of growth (and hence the latent-heat evolution) is slow, allowing large numbers of substrates to become active. The reverse is true when the GRF is small [1, 2]. Easton and St John [7] in their model confirmed that the GRF represents the rate of development of the constitutional zone with respect to the fraction of solid at a zero fraction of solid. In other words, it is a measure of how rapidly the constitutionally under-cooled zone is formed at the earliest stages of growth.

The influence of alloying elements in aluminum on the grain size has also been experimentally studied [5, 6, 8-14]. The data shows that the grain size decreases significantly with an increasing GRF. It is important to point out that the majority of the previously mentioned grain-refining tests were made at cooling rates ranging from 0.5 to 5 °C/s. The results of Backeroud and Johnsson [12] reveal that increasing the GRF shows a reduced effect of grain refinement at higher cooling rates. The aim of this work is to present the results of the grain refinement of samples with different GRFs made at faster cooling rates (15 °C/s) and compare them with the results from slower cooling rates.

EXPERIMENTAL

Commercial purity aluminum (99.8 wt.% Al), an Al-Fe alloy and an AlTi5B1 commercial grain refiner (in the form of 9.5-mm-diameter wire) were used in this study. The chemical compositions of the aluminum, the
Al–Fe alloy and the AlTi5B1 grain refiner are presented in Tables 1 and 2.

Three kilograms of aluminium and the Al–Fe alloy were melted in a medium-frequency induction furnace with a graphite crucible. Grain refiners were added at a temperature of 705±5 °C. The melts were stirred with a graphite stick and 2 min after the addition of the grain refiners they were cast into a bronze mould (cooling rate ~15 °C/s), as presented in Figure 1. The castings were cut 13 mm above the base for the preparation of samples for metallographic examination.

Samples for microstructure analysis were ground, polished and anodized for 2 minutes at 23 V in a 2.5 % water solution of HBF4 for polarized-light microscopy. The average grain areas were measured on polarized-light microscopy images using commercial software for the image analysis. The average grain areas were converted to the mean, linear-intercept lengths in accordance with ASTM E112-96. The term “grain size” in this paper corresponds to the mean, linear-intercept length.

RESULTS AND DISCUSSION

The results of the grain refinement of the aluminium and the Al–Fe alloy with the AlTi5B1 grain refiner are presented in Table 3 and Figure 2. The titanium and boron contents in the samples presented in Table 3 are based on the actual chemical analysis of each sample. The content of “free” titanium presented in Table 3 was calculated on the basis of the titanium and boron contents in the sample and the assumption that all the boron forms TiB2. The GRF was calculated according to equation (1). Besides the “free” titanium, the silicon, iron and vanadium contents were considered in the case of the aluminium, and the silicon, iron, copper, manganese and...
vanadium contents in the case of the Al-Fe alloy. The slopes of the liquidus \( m \) and the equilibrium partitioning coefficients \( k \) used in the calculation of the GRF were obtained from the work of Easton and St John [7].

With increasing boron content, as a consequence of the addition of the AlTi5B1 grain refiner, the grain size decreased in both the aluminium and the Al-Fe alloy (Figure 2). In the presented range of boron content the grain size is smaller in the case of the Al-Fe alloy. The difference in the grain size between the aluminium and the Al-Fe alloy for the same boron content is approximately 15 \( \mu m \) (Figure 2). The boron contents in samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3). The GRFs for the samples A2 and F4 were 0.0012 wt.% and 0.0011 wt.%, and are comparable (Table 3).

A comparison of the efficiency of the grain refiners for the same level of titanium addition shows that the AlTi3C0,15 or AlTi5C0,2 grain refiners are more efficient at slow cooling rates and larger additions [16, 17], while at fast cooling rates the AlTi5B1 is much more efficient [18-20]. These results were also confirmed by the results of the performance of the AlTi5B0,2 and AlTi5C0,2 grain refiners in twin-roll strip casting [21, 22]. The results of the performance of the grain refiners at different cooling rates can be explained by the effect of the solutes on the grain refinement at different cooling rates. The grain refiners AlTi3C0,15 or AlTi5C0,2 contain larger contents of “free” titanium in comparison to the AlTi5B1, and consequently this solute titanium acts as a more efficient grain refiner at slower cooling rates than at faster cooling rates, as shown in Table 4.

**CONCLUSIONS**

Aluminium and an Al-Fe alloy were grain refined with different additions of AlTi5B1 grain refiner at cooling rate of 15 \( ^\circ C / s \). We found that the grain size decreased with increasing boron content in both the aluminium and the Al-Fe alloy. We also found that the grain size in the investigated range is, for the same boron content, smaller in the case of the Al-Fe alloy. A difference of approximately 15 \( \mu m \) was found between the grain sizes for the same boron content in the aluminium and the Al-Fe alloy.

**REFERENCES**


Note: Linguistic Adviser / English language Paul McGuiness, Ljubljana, Slovenia.