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New developments on optimizing properties of high-Zn aluminium cast alloys

W.K. Krajewski[1], J. Buras[1], P.K. Krajewski[1], A.L. Greer[2], P. Schumacher[3], K. Haberl[3]

[1]AGH University of Science and Technology, Faculty of Foundry Engineering, 23 Reymonta Street, 30-059 Krakow, Poland
[2]University of Cambridge, Department of Materials Science & Metallurgy, 27 Charles Babbage Road, Cambridge CB3 0FS, UK
[3]University of Leoben, Department of Metallurgy - Chair of Casting Research, Franz-Josef-Strasse 18, 8700 Leoben, Austria

[1]krajwit@agh.edu.pl

Abstract. Foundry alloys with Al-based matrices have a wide range of uses in today's global economy and there is a high demand for castings of Al alloys, including Al-Zn alloys. In this paper, investigations on the grain refinement of high-Zn aluminium cast alloys are presented. Aluminium alloys with relatively high zinc content have a tendency to be coarse-grained, especially in the case of castings with low cooling rates such as are found in sand moulds. The coarse-grained structure degrades the plasticity, specifically the elongation. Therefore, for aluminium alloys of high (10-30 wt.%) zinc content, inoculation is attractive, aiming to break up the primary dendrites of the α-phase solid solution of zinc in aluminium. Such dendrites are the principal microstructural component in these alloys. On the other hand, a finer grain structure usually reduces the damping (e.g. as measured by attenuation of ultrasound) in these alloys. In the present investigations, a binary sand-cast Al-20 wt.% Zn alloy was inoculated with different additions of AlTi3C0.15 (TiCAl) and ZnTi-based master alloys. The sand-cast samples were subjected to mechanical-property measurements (tensile strength and elongation), image analysis to determine grain size, and measurements of the attenuation of 1 MHz ultrasound. It is found that both of the master alloys used cause significant refinement of the α-AlZn primary dendrites and change their morphology from linear-branched to semi-globular, increase the elongation by about 40%, and decrease the attenuation coefficient by about 25% in comparison with the initial alloy without inoculation.

1. Introduction

Grain refinement of non-ferrous cast alloys, mainly those based on Al, is a common practice, which allows fine microstructures to be obtained with increased ductility [1–8].

Cast alloys based on Al and Zn are classified as structural materials with good damping capacity. In particular, high-Al zinc alloys, for example ZA-27, fall in the category of HiDAlloys (high-damping alloys) [9]. It has also been noted that high-Zn aluminium alloys show high damping, good tribological properties and high fatigue strength [10-12]. Grain refinement has been used for zinc-aluminium alloys with high Al content of 15-30 wt.% Al [13–18]. In fact, both groups, i.e. high-Al zinc and high-Zn aluminium alloys, solidify naturally with a coarse structure and a refinement process is necessary to permit highly refined structures to be obtained [18–22]. In practice, there are two main groups of refiners based on the Al-Ti-B and Al-Ti-C systems, commonly used in the casting of Al-alloys. A newly introduced alternative – a master alloy based on the Zn-Ti system – requires a melt temperature of only about 500^{o}C, thus avoiding detrimental overheating, reducing the costs of energy and material, and improving the mechanical properties of the castings [17-18, 23-25]. On the other hand, many structural materials are required to have good damping properties, and unfortunately a fine grain structure is believed to reduce the damping capacity [26-28]. The present paper summarizes work on the grain refinement and damping-property measurements of high-Zn aluminium cast alloys on the basis of joint investigations performed over the last ten years at AGH University of Science and Technology – Faculty of Foundry Engineering, University of Cambridge, UK – Department of Materials Science and Metallurgy, and at University of Leoben – Department of Metallurgy, Chair of Casting Research.

2. Experimental

The alloys Al-(18-22)%Zn (Al-20Zn) and master alloy (Zn,Al)-4%Ti were melted from elements of minimum purity 99.9 % (all compositions in wt.%). Melting was performed in an electric furnace with an argon protective atmosphere, in a clay-graphite crucible of 2-litre capacity (the details of melting and casting are given in Refs [6–8]). During these experiments an amount of the ZnTi-based master alloy or Al-3Ti-0.15C (TiCAl) was added to the melt to introduce 25, 50, 100, 200 or 400 ppm of Ti. The inoculated melt was held for about 2–3 minutes to ensure complete dissolution of the added master alloy. Next, the melt was stirred for about 2 minutes with a silica-glass tube, and finally the alloy was cast into dried sand moulds to obtain dog-bone-shape samples (gauge section ∅12x60 mm) for tensile and structural tests, Fig. 1 (a) – (b) as well as ∅32x80 mm samples for structural and damping tests.

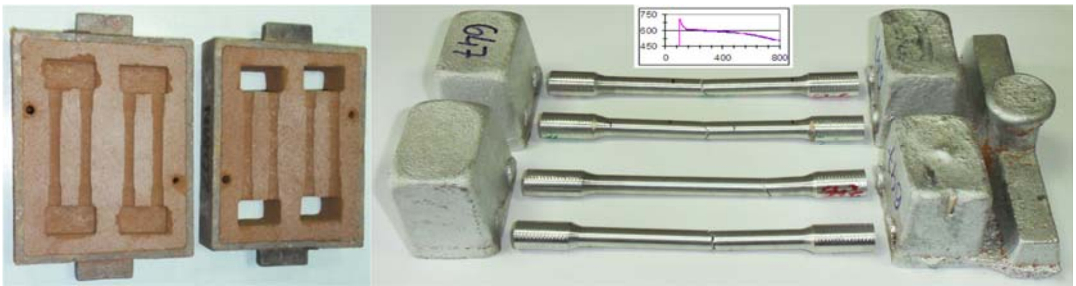


Figure 1. (a) Sand mould for tensile strength and elongation measurements ; (b) Machined specimens after UTS tests with risers and gating system.

Optical light metallography (LM) was performed using a Leica DM IRM microscope. Scanning electron microscopy (SEM) was performed on unetched samples with a Philips XL30 microscope equipped with an energy dispersive X-ray EDX spectrometer (Link-Isis). Damping-coefficient tests were carried out using the ultrasonic Krautkramer measurement set, model USLT 2000. The entire study was conducted for 1 MHz longitudinal waves, using the MK1S mini-transducer with head diameter of 10 mm. To determine the attenuation intensity, the echo method (*pulse-echo method*) was adopted, using the internal software of the Krautkramer USLT 2000 device. Prior to testing, the device was calibrated with a pure-zinc cast sample.

3. Results and Discussion

Grain refinement of the high-zinc molten alloys by the (Zn,Al)-4Ti and TiCAl master alloy is very effective, as can be clearly seen in Fig. 2 (a) – (d) and Fig. 3 (a) – (b). At the same time, the elongation significantly increases while the tensile strength remains basically preserved (Fig. 6).

As noted in the introduction, the main refiners for Al alloys are those based on the systems Al-Ti-B and Al-Ti-C. For the Al-Ti-C master alloy, TiC is the direct nucleant particle for α-Al. This is because of the similar crystal structure and lattice parameters of α-Al and TiC (Table 1).

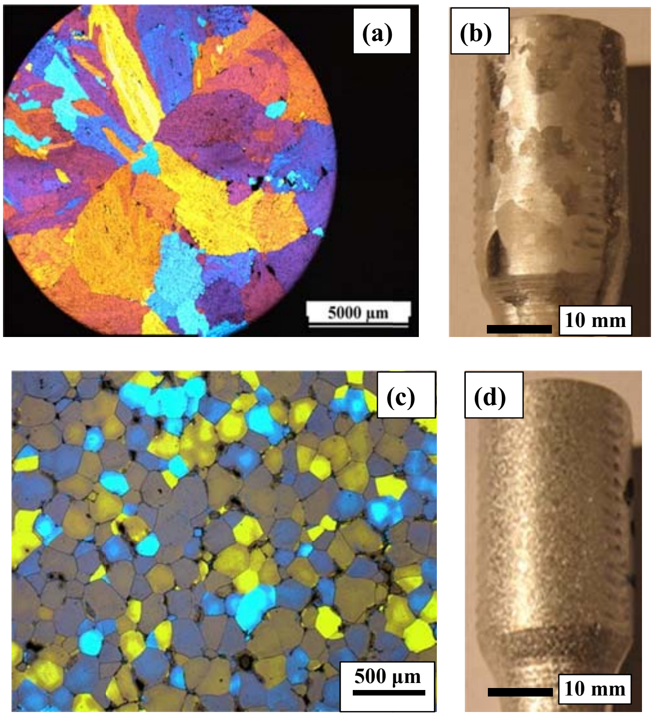


Figure 2. LM pictures of macrostructures and microstructures of the Al-20Zn alloy. (a) and (b) initial alloy; (c) and (d) alloy inoculated with (Zn,Al)-Ti4 MA – 0.04 wt.% Ti; (a) and (c) ground, polished and etched surfaces of a section [19-22]; (b) and (d) surfaces of the tensile samples.

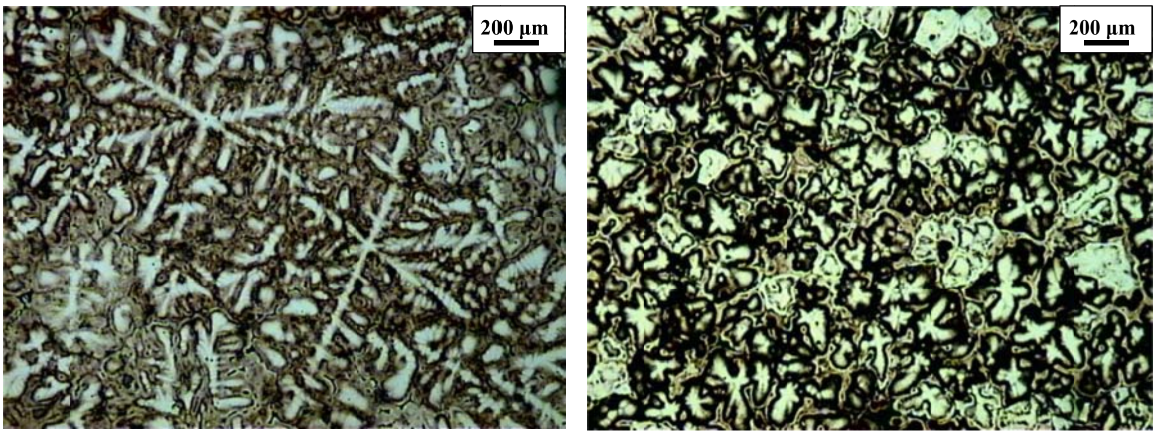
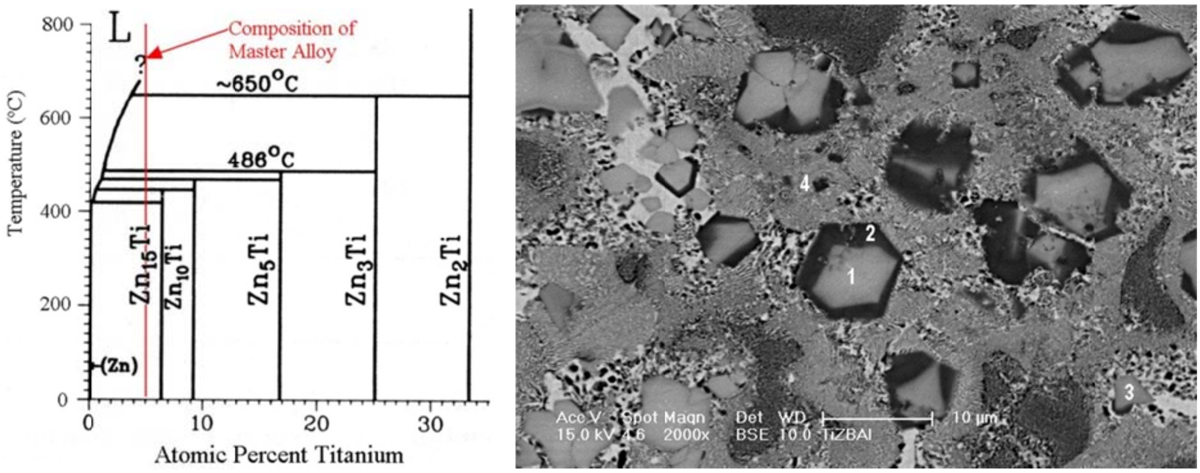


Figure 3. Changes of microstructure of the Al-20Zn alloy. (a) initial alloy without Ti addition, (b) the same alloy doped with 50 ppm Ti introduced with the Al-3Ti-0.15C (TiCAl) grain refiner, Light microscopy [25-26].

The new family of grain refiners presented here, based on the Zn-Ti system, contain $TiZn_3$ phase in their structure (Fig. 4), which has the same crystal symmetry as α-Al and closely matches its lattice parameter. In an Al-Zn melt the $TiZn_3$ phase transforms into the ternary, more stable, $Ti(Al,Zn)_3$, which has also the same features as $TiZn_3$, and whose particles appear to be active centres of heterogeneous nucleation in inoculated Zn-Al alloys [21-22]. This is the most probable reason why the ZnTi-based master alloys are effective as refiners of the present Al-Zn alloys. Macrostructures and microstructures shown in Figs 2 and 3 indicate that the ternary master alloys AlTi3C0.15 and (ZnAl)-Ti4 cause strong refinement of the inoculated AlZn20 alloy. It should be noted that the ZnTi-based master alloys have a mass density higher than the inoculated Al-20Zn alloy, which simplifies their introduction into the melt. They dissolve very quickly already at temperatures of 500°C, allowing aluminium-zinc alloys to be treated without the detrimental overheating that is required when using Al-Ti based refiners.

Table 1. Crystallographic comparison of nucleants and the α-Al phase.

Phase	Crystal structure	Lattice parameters (a), [nm]	Lattice misfit (δ), [-]
α(Al)	Cubic A1	a = 0.4043	---
TiC	Cubic B1	a = 0.4328	1.034
$TiZn_3$	Cubic $L1_2$ ($AuCu_3$ type)	a = 0.39424	0.9874
$Ti(Al,Zn)_3$	Cubic $L1_2$ ($AuCu_3$ type)	a = 0.3958	0.9894



(a) (b)

Figure 4. (a) Zn-Ti binary system and (b) SEM (backscattered electron) image of (ZnAl)–4 wt.%Ti master alloy [18].

Table 1. Chemical composition of the randomly chosen particles of Ti-Al-Zn shown in Fig. 5 of ~$Ti(Al,Zn)_3$ stoichiometry. EDAX-GEMINI 4000 EDS [18].

No.	Ti	Zn	Al
1	24.4	66.0	9.5
2	21.9	16.8	61.3
3	23.8	67.6	8.6
4	23.3	16.3	60.4

From Fig. 5, it can be seen that the 2D (planar) mean grain diameter decreases from about 2300 µm for the alloy without inoculation to about 180 - 150 µm for the same alloy doped with 50 – 100 ppm Ti introduced with the TiCAl or ZnTi-based master alloys. The grain refinement that is obtained allows the elongation to be increased by about 40%, i.e. from 1.7 to 2.4%, with the tensile strength of 230-250 MPa practically preserved (increase by 5-10%) (Fig. 6).

On the other hand, in the grain-refined alloys, the attenuation coefficient of 180 – 190 dB/m is decreased by ~20-30% in comparison to the initial alloys without inoculation (220 - 240 dB/m). However, the attenuation coefficient of the refined alloys is still high, remaining on a level typical for high-damping alloys.

However, the obtained results clearly show that the level of grain refinement should be a compromise to balance good ductility with good damping, thus optimizing the combination of mechanical properties.

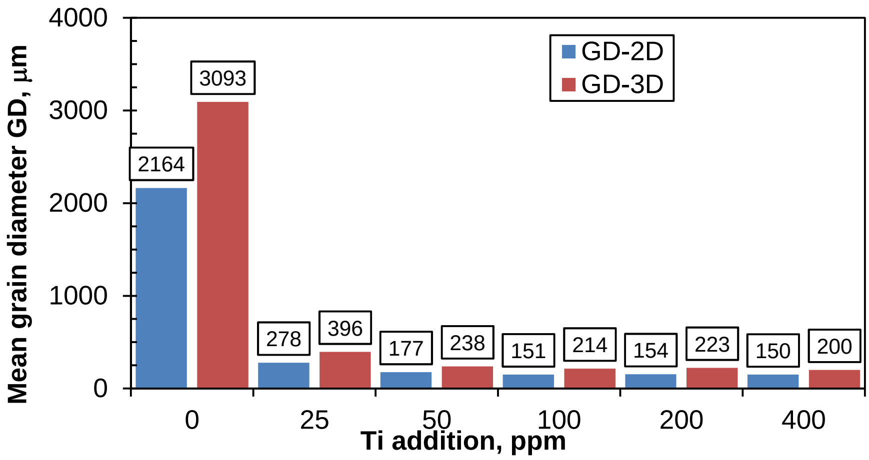


Figure 5. Influence of small Ti addition introduced with TiCAl master alloy on the Al-20Zn alloy mean grain diameter (GD). GD-2D is a planar grain diameter evaluated from the intercept method. GD-3D is a mean space (volumetric) grain diameter calculated from the Voronoi formula [21, 28].

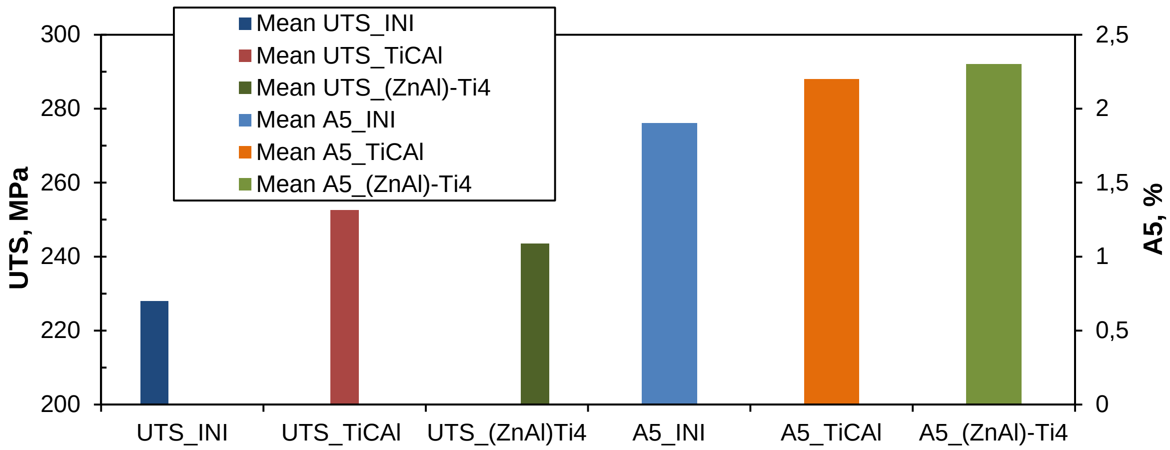


Figure 6. Tensile strength (UTS) and elongation (A5) of the Al-20Zn alloy inoculated with Al-3Ti-0.15C (TiCAl) and (ZnAl)-Ti4 master alloy.

4. Conclusions

Based on the studies described above, the following conclusions can be drawn:

For the high-Zn aluminium alloys in this study, grain refinement is a promising process leading to property improvements. At the same time, using the low-melting-point (Zn,Al)-Ti-based master alloys avoids the excessive melt overheating needed for the TiCAl or TiBAl refiners and reduces the possibility of gas pick-up and material loss.

It was also noted that grain refinement decreased the attenuation coefficient of 1 MHz ultrasound by about 25%. Taking this into account, it is concluded that further studies of other property changes, e.g. creep and tribological properties, would be desirable.

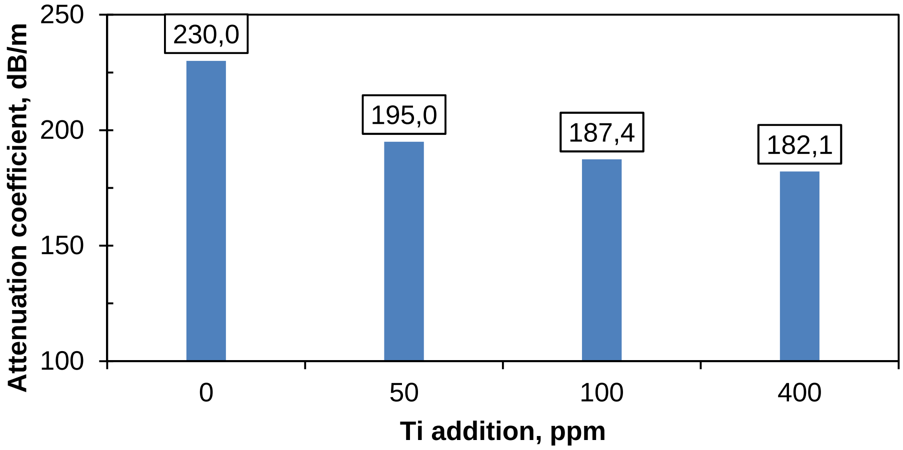


Figure 7. Influence of small Ti addition introduced with TiCAl master alloy on the damping properties of Al-20Zn alloy. Krautkamer USLT2000 – ultrasound of 1 MHz frequency [20-21].

Acknowledgements

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