Semi-solid Casting of High-reactive Wrought Alloys by Means of the Alloy AlLi2.1Mg5.5ScZr (AA1420*)

Matthias Bünck[1,a], Fabian Küthe[1,b], Andreas Bührig-Polaczek[1,b],
Alexander Arnold[2,c], Bernd Friedrich[2,d] and Roger Sauermann[3,e]

[1]GI Foundry Institute, RWTH Aachen

[2]IME Process Metallurgy and Metal Recycling, RWTH Aachen

[3]Otto Junker Group

[a]m.buenck@gi.rwth-aachen.de, [b]sekretariat@gi.rwth-aachen.de, [c]aarnold@ime-aachen.de,
[d]bfriedrich@ime-aachen.de, [e]ros@otto-junker.de

Abstract. Semi-solid forming offers new potentials for processing of high reactive and hot crack susceptible aluminium-lithium wrought alloys. With the tailored alloy AA1420* (AlLi2.1Mg5.5 +Sc+Zr) a promising material for thixoforming with achievable high strength of up to 500MPa tensile strength and over 400MPa yield strength concomitant with its low density of 2,46g/cm^3 is achievable. Due to high solid fractions the effect of solidification shrinkage could be sufficiently decreased with the result of hot-tear-free casting.
Simulation supported a critical to cast automotive tie rod was exemplarily manufactured via semi-solid-technology with promising results.
Furthermore with an improved and advanced heat treatment enhanced mechanical properties, comparable to those of rolled AA1420, were achieved.

Introduction

Wrought alloys generally feature high strength compared with excellent plasticity, but in classical forming processes like forging or rolling the freedom of shape is restricted. This constriction limits the application of those alloys to relative simple geometries. Conventional casting of wrought alloys is generally not possible, because of the hot tearing susceptibility. Due to these limitations a niche for SSM-processing is given, because with higher solid fractions the effect of volume shrinkage on tearing is significantly reduced. Thus in the majority of cases wrought alloys are under certain conditions semi-solid castable free from defects.

Another advantage of semi-solid forming is the reduced processing temperature compared to fully liquid casting. Hence the reactivity of oxygen-affine elements is significantly reduced. Additionally the life-cycle of the forming tools can be extended.

Regarding this benefits semisolid casting of wrought alloys, especially of high reactive wrought alloys appear expedient. In this research work the aluminium-lithium-magnesium super-light-alloy AA1420 was chosen and tailored for thixocasting by adding scandium and zirconium. By means of the thixocasting process and the rheo container process (RCP) the suitability of this alloy for SSM-processing was investigated.

DoE-supported synthesis of Al-Li-Mg-based precursor material

The benefits of Al-Li alloys are the excellent mechanical properties/density and Young's modulus/density ratios compared to conventional aluminium alloys (density of Al-Li: 2.3-2.5 g/cm^3). Due to this, the disadvantage of higher costs for manufacturing of precursor materials and also forming, caused by the high reactivity of the alloying elements Li and Mg, is compensated by the demands of aerospace applications, where even small weight reductions result in high added values.

For SSM-forming, globular grained feedstock materials are necessary. To guarantee the filling of small mould-areas, small globule grain sizes have to be assured (typically less than 100μm, [1]). Regarding this, up to 0.3 weight-% scandium and zirconium were added to the conventional wrought alloy AlLi2.1Mg5.5 (AA1420), because of their positive effects on the grain size. In order to investigate its influence on the grain size during feedstock material production, the casting temperature was also varied (750°C, 800°C, and 850°C). With the aid of the DoE software MODDE 5.0$^{©}$, billets with variations in chemical composition were molten and cast as precursor material for subsequent semi-solid processing. As the result of high reactivity of lithium with atmospheric gases and refractory material and its high equilibrium vapour pressure a lithium-resistant SiC-crucible was required and installed in a 3-bar argon overpressure induction melting furnace. The pouring of the 3kg billets took also place under protective gas.

The resulting effects of the Sc and Zr addition on the grain size in the as-cast condition are shown in Fig. 1. It illustrates the statistical significance, while in contrast the variation of the casting temperature has almost no influence on the grain size, Fig. 2. It also shows the contents of Sc and Zr needed to achieve a certain grain size. The mathematical model predicts a grain size of 30μm starting from contents of 0.25% Sc and 0.25% Zr. The strongest effects on grain size were observed when both elements (Sc and Zr) were added to the Al-Li-Mg matrix.
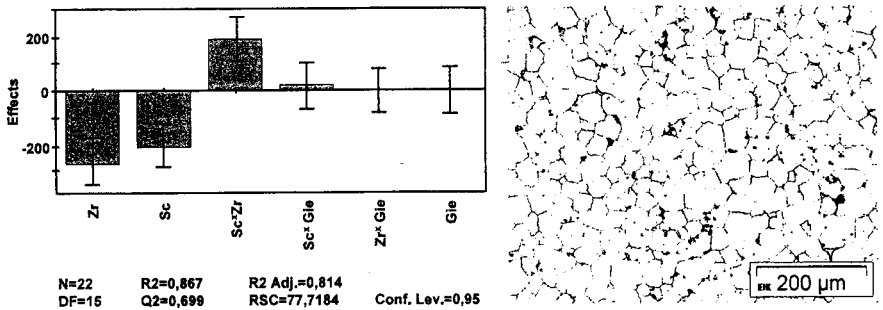

Fig. 1: Statistical effects of Sc and Zr addition (single addition and mixture) and the casting temperature (Gie) on the grain size of the alloy AlLi2.1Mg5.5ScZr (left); example of the microstructure of a billet (right).
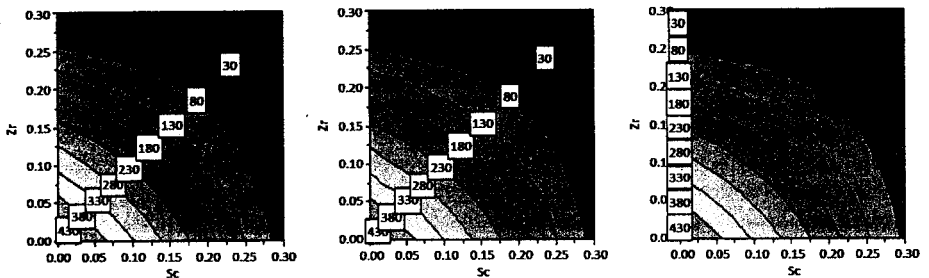

Fig. 2: Dependence of the average grain size in μm on Sc and Zr contents for the alloy AlLi2.1Mg5.5ZrSc at 3 different casting temperatures (left: 750°C; centre: 800°C; right: 850°C).

RCP – Rheocasting of high reactive alloys

The special feature of the Rheo-Container-Process (RCP, [2,3], Fig. 3) is the encapsulation and consequently the suitability for processing of highly reactive alloys such as magnesium or aluminium-lithium alloys. To diminish the atmosphere contact of a high oxygen affine alloy the slightly superheated molten metal is poured directly into a 1mm-walled aluminium can (container), ensuring wall contact during melt inflow for nucleation. At first contact with the room-tempered

container wall, seed crystals are built and subsequently, because of the flowage, finely dispersed in the container. The heat capacity of the container suffices to cool the melt below liquidus. Due to this, and as the result of a high grain density, a globular microstructure forms. Therefore the container is placed directly after pouring into a cooling device and covered immediately afterwards and admitted with argon-atmosphere to prevent burn off. To minimise the process time the container is cooled with compressed air, [4]. At target temperature, respectively at the desired solid-fraction, the container is transferred, together with the semi-solid billet, to the shot chamber of a high-pressure die-casting machine and pressed into the die. The folded container remains completely in the biscuit [5].
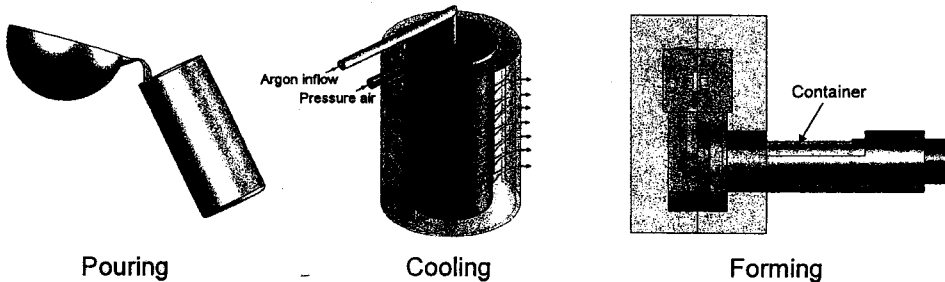

Fig. 3: The Rheo container process schematically

The use of the non-returnable container, consisting of 99.5%-aluminium, avoids recycling [6]. Apart from this the usage of steel cans etc. is also possible and imaginable for rheocasting of high melting metals, and in particular for steel. Conventional 1mm-walled aerosol-can-blanks, with 80mm in inner diameter and with a total length of 280mm were chosen, because of their exact suitability for the thixo shot sleeve of the high-pressure die-casting machine.

Reheating of the billet for Thixocasting

All thixo-billets were reheated using an AEG Elotherm reheating device of the type ETH 1 coupled to the software Diadem. At the target temperature (after a 120s long homogenisation period), the billets were transferred manually to the shot sleeve of a high-pressure die-casting machine (type Bühler H-630 SC) and formed directly.

To prevent the oxidisation of the AA1420*-billets during reheating, the billets were wrapped into aluminium foils.

Forming experiments: step form and tie rod

Preliminary forming investigations by means of the step die have in the first instance shown the suitability of the rheo container process, [7]. To evaluate the usability also for industrially manufactured real components, comprehensive casting tests were conducted.

As a demonstrator component a tie rod was chosen (Fig. 4) with a minimum thickness of 2.5mm at a total length of 400mm and a weight of approx. 350g (A356). Due to the challenging castability, it was appropriate to investigate the difficult to cast aluminium-lithium wrought alloy AA1420*, [8]. The mould was adjusted regarding the rheological behaviour of semi-solid suspensions. The ingate was modified to warrant a laminar flow of the semi-solid metal. The bearings of the tie rod excite a critical two-channel flow at both ends of the component, which result in cold runs or oxide layers.

Rheo container process: experiments and results

The tailored precursor AA1420*-ingot was molten under protective gas, poured at 630°C into the container and processed at a temperature of 600°C, respectively at a solid fraction of 0.5 (calculated

by ThermoCalc) in the HPDC-machine. Manufactured tie rods were microscopically analysed and heat treated as well as tensile tested. During HPDC-processing rapid solidification of the remaining melt took place in non-equilibrium by the formation of "unexpected" eutectic, including the phases Al_2LiMg, $Al_{12}Mg_{17}$ and Al_8Mg_5 [9]. While heat treatment for 24 hours at 460°C – the solidus temperature was carried out by DTA-analysis and detected at 480°C - these phases (Al_2LiMg, Al_8Mg_5, $Al_{12}Mg_{17}$) were to a large extent dissolved in the alpha solid solution, leading to a more or less single phase structure (cp. Fig. 4). The added elements Sc and Zr formed $Al_3(Sc_xZr_{1-x})$ dispersoids, which inhibited undesired grain growth during the solution treatment [10,11]. After water quenching from the solution temperature the components were aged for 17 hours at 160°C under argon atmosphere. According to literature, the primary strengthening phase Al_3Li was formed [10].
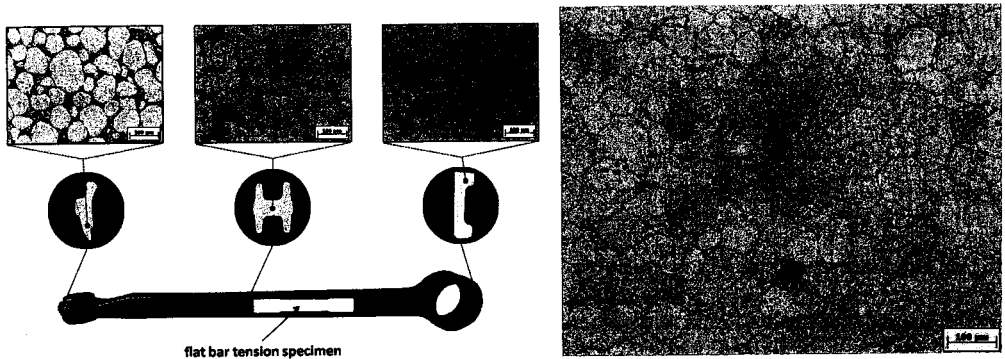

Fig. 4: Microstructure of semi-solid cast Zr/Sc-microalloyed AA1420[*]: homogeneity sampling position of the flat bar tension specimen (left); right hand side: microstructure of heat treated sample. The black dots are $Al_3(Sc_xZr_{1-x})$ particles (proved with EDX). At the grain boundaries Al_2LiMg-dispersoid-accumulations were detected via EDX.

Out of the cast tie rods, flat bar tension specimens were sectioned and tested. Fig. 4 shows the sampling locations and the good homogeneity of the microstructure over the total length of the component. Via heat treatment the mechanical properties of AA1420[*] were improved significantly. In this way the tensile strength was increased to over 400MPa, the yield strength up to 250MPa, and the elongation to fracture to an average of 6.4%, almost three times higher than in the thixocast condition, [8]. Chemical analyses showed that the tie rods were manufactured homogeneously, [8]. To investigate the improvement potentials of the heat treatment, sectioned samples of the connecting rod were solution-annealed (24h at 460°C), quenched in water and subsequently aged for various times in an oil bath at different temperatures (140°C, 160°C, 180°C) at the Swiss Federal Institute of Technology (ETH) Zurich. The pyramid diamond hardness (HV5) was measured and plotted against ageing time. The hardness before heat treatment was 84 HV and after solution annealing 94 HV. While increasing the ageing temperature, the maximum of hardness (130 HV in each experiment) requires shorter ageing time. In order to achieve a maximum hardness, the following annealing parameters are advisable: 180°C/10h, 160°C/25h or 140°C/>35h, [8]. This revised heat treatment was tested during thixo casting experiments with the modified AA1420. Despite casting in the semi-solid state hot cracks appear at the bearing points. To solve this problem, simulations regarding the hotspots at the bearings were conducted using MAGMAsoft and verified during thixocasting of AA1420[*].

Thixocasting: experiments and results

The as-cast feedstock billets were turned off to a diameter of 78mm and a length of 160mm for the thixoforming process. By means of MAGMAsoft simulations the hot-tear problem was solved. Because of the non availability of thermo-mechanical data of AA1420*, A356 was used as cast alloy for the simulations. A removable steel core was used for building up the big bearing. If the steel core was hot, a hot spot directly behind the core was the result. Otherwise with a cold steel core the hot spot is displaced into the over flow. The simulation result using a 60°C cold steel core compared to a 300°C hot steel core show this effect, Fig. 5. Regarding this, the steel core was cooled before each shot. The effect of this is visualised in Fig. 6. Decreasing the core temperature, the hot tearing tendency also decreases. Using a cold core that was inserted only directly before forming, no more hot tear appears.
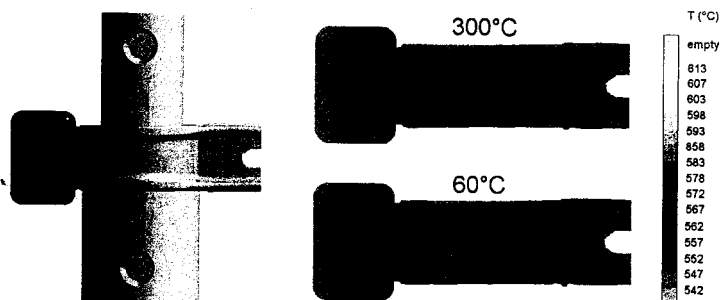

Fig. 5: MAGMAsoft-simulation: comparison between steel core temperature: 60°C and 300°C; the simulation shows the displacement of the hot spot
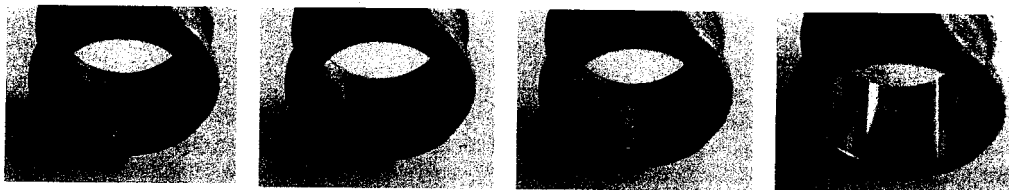

Fig. 6: Hot tearing at the big bearing point: From left to right: a decreasing steel core temperature results in a decreasing hot tear tendency

A total of 12 tie rods were cast and consecutively numbered with T1 to T12. The samples T1 to T3 were not further treated. All other samples were heat treated under argon atmosphere. At first all nine samples were solution annealed for 24 hours. With reference to the improvement tests at the ETH Zürich the samples were aged afterwards: the samples T4-T6 were aged for 10 hours at 180°C, T7-T9 were aged for 25 hours at 160°C, and T10-T12 were aged at 140°C for 35 hours. As shown in Fig. 4 flat bar tension specimens were taken from both sides of the double-T beam of the tie rods (6 samples per treatment condition) and tensile-tested. The results are illustrated by means of a bar diagram, Fig. 7.

Due to the heat treatments a high increase of the mechanical properties could be achieved. As a result of the longer ageing time, concomitant with the reduced ageing temperatures the elongation to fracture decreased; notwithstanding the strength remain at a similar level. The mechanical properties were raised during the heat treatment to almost 500MPa tensile strength and the yield strength to a top of 437MPa. The elongation to fracture could be doubled during the ageing at 180°C from averaged 1.57% to 2.98%, but these results fall short of the expectations (cp. results of the RCP experiments).
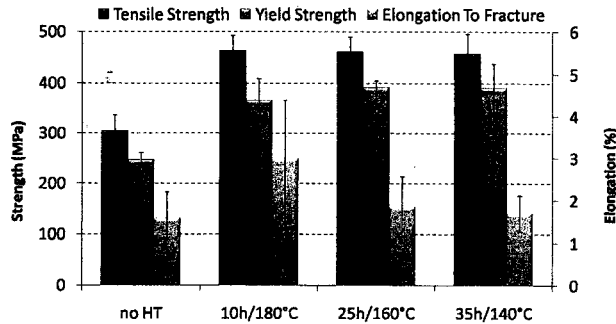
Fig. 7: Mechanical properties of thixo-cast AlLi2.1Mg5.5ScZr; all heat treated samples were solution annealed at 460°C for 24 hours (HT – heat treatment).

Assessment and outlook

Depending on the cast part, defect free SSM-casting of AA1420* is possible. Indeed, experiments have shown that mould adjustment is of utmost importance, especially at hot tear susceptible areas. In the process excellent mechanical properties of cast AA1420*, comparable to those of rolled AA1420 were achieved. As a result semi-solid processed AlLi2.1Mg5.5ScZr may be used near net shape for aerospace applications. It may also be expected that the found results are usable also for other wrought alloys. Hence SSM-forming is a suitable process route for casting of wrought alloys.

References

[1]   D. Apelian: 'Semi-Solid Processing Routes and Microstructure Evolution', Proceedings of the 7th S2P Int. Conf., Tsukuba, Japan, 2002, pp. 25-30

[2]   Fehlbier, M.; „Herstellung, Charakterisierung und Verarbeitung teilflüssiger metallischer Werkstoffe verschiedener Aluminium- und Magnesiumlegierungen", PhD thesis RWTH Aachen, Shaker Verlag, 2003

[3]   Aguilar, J.; Fehlbier, M.; Grimmig, T.; Bührig-Polaczek, A., „Processing of semisolid Mg alloys", Proceedings of the 8th S2P Int. Conf., Limassol, Cyprus, 2004.

[4]   Bünck, M.; Warnken, N. Bührig-Polaczek, A.; 'Defining the boundaries of globular to dendritic transition of A356 in the cooling channel process'; Proceedings of the 5th Dec. Int. Conf. SP07; 2007; pp. 615-619

[5]   Aguilar, J.; Grimmig, T.; Bührig-Polaczek, A.: "Rheo-Container-Process (RCP): New Semisolid Forming Method for Light Metal Alloys", Proc. of the 6th Int. Conf. Magnesium Alloys and their Applications, DGM, 2003, 767-773

[6]   Grimmig, T.; Aguilar, J.; Bührig-Polaczek, A.: "Optimization of the rheocasting process under consideration of the main influence parameters on the microstructure", Proceedings of the 8th S2P Int. Conf., Limassol, Cyprus, 2004

[7]   Sauermann, R; Friedrich, B.; Grimming, T.; Bünck, M.; Bührig-Polaczek, A.: "Development of Aluminium-Lithium alloys processed by the Rheo Container Process", Proceedings of the 9th S2P Int. Conf., Busan, Korea, 2006, pp. 513-517

[8]   Sauermann, R.; Friedrich, B.; Bünck, M.; Bührig-Polaczek, A.; Uggowitzer, J.: „Semi-Solid Processing of Tailored Aluminium-Lithium Alloys for Automotive Applictions", in Advancecd Engineering Materials 2007, 9, No. 4, pp.253-258, WILEY-VCH Verlag Weinheim

[9]   Belov, N.A.; Eskin, D.G.; Aksenov, A.A.; "Multicomponent phase diagrams: applications for commercial aluminium alloys", Elsevier Ltd., 2005, p. 261

[10]   Eswara Prasad, N.; Gokhale, A.A.; Rama Rao, P.; "Mechanical behaviour of aluminium-lithium alloys", Sãdhanã Vol. 28, Parts 1 & 2, 2003, pp. 209-246

[11]   Raade, G.; "Scandium", Chemical & Engineering News Vol. 81, American Chemical Society, 2003, pp. 66-68