Development of Al-Li-based Alloys for thixo-formed Automotive Parts

R. Sauermann, A. Arnold, B. Friedrich[1]; B. Hallstedt, J.M. Schneider[2]

[1] IME Process Metallurgy and Metal Recycling, RWTH Aachen University
[2] MCh Materials Chemistry, RWTH Aachen University

Abstract

This investigation gives a contribution to the development of light weight / high performance Aluminum-Lithium alloys tailored for semi-solid processing. Thermochemical calculations identified important key values like solidus liquidus interval, fraction solid versus temperature and phase reactions. The synthesis of Sc and Zr micro-alloyed Al-Li precursor billets was performed by overpressure induction melting in controlled atmosphere in order to tune the thixoforming and mechanical properties. Microstructure investigations on Al-Li specimens were carried out as well as measurements of the mechanical properties. With the aid of the microalloying elements Scandium (0,3 wt%) and Zirconium (0,3 wt%) a mean diameter of uniform globular grains in the range of 30µm was obtained. The static properties in the as cast are compareable to the conventional AlSi7Mg0,3 semi-solid standard alloy in T6 heat treatment condition (TS~260MPa, UTS~310MPa, A~7%), but related to the density the investigated Al-Li alloys have better strength to weight ratios. Therefore further potential in improving mechanical properties can be expected after heat treatment of the manufactured Al-Li-Mg precursor materia. It is shown that specifically developed Al-Li alloys offer a great potential for semi-solid manufacturing and subsequent application as automotive components.

1 Introduction

The semi solid technology (also called "thixo-forming") is defined by a processing of metals in the suspension state between solidus and liquidus temperature [1,2,3]. This process can be placed between fully liquid casting on the one hand and solid forming on the other hand. Via thixoforming it is possible to produce near-net shape components with enhanced mechanical properties due to the reduced entrapped gas content and reduced solidification shrinkage, leading to lower porosity volumes. "Thixocasting" and "Thixoforging" are currently the two metal shaping methods where the characteristics of semi solid metal suspensions (slurries) are exploited. Compared to conventional die casting the following advantages of semi-solid forming are known:

- Thick and thin walled structures can easier be produced
- Cast and wrought alloys can be processed

- Globular microstructures are obtained leading to homogeneous properties
- Less porosity volume leading to improved pressure-tightness and heat treatment is applicable
- processing of high reactivity alloys is possible due to lower process temperature

Aluminum-lithium alloys have been developed primarily to reduce the weight of aircraft and aerospace structures. The major development work began in the 1970´ies, when aluminum producers accelerated the development of aluminum-lithium alloys as replacements for conventional airframe alloys. Commercial aluminum-lithium alloys are targeted as advanced materials for aerospace technology primarily because of their low density, high specific modulus, and excellent fatigue and cryogenic toughness properties such improving the performance of the aircraft. The superior fatigue crack propagation resistance of aluminum-lithium alloys, in comparison with that of traditional 2xxx and 7xxx alloys, is primarily due to high levels of crack tip shielding, meandering crack paths, and the resultant roughness-induced crack closure. The principal disadvantages of peak-strength aluminum-lithium alloys are reduced ductility and fracture toughness in the short transverse direction, anisotropy of in-plane properties, the need for cold work to attain peak properties, and accelerated fatigue crack extension rates when cracks are micro structurally small. Also reduced corrosion resistance due to the enhanced reactivity of the main alloying element Lithium has to be taken into consideration for the desired application.

The development of commercially available aluminum-lithium-base alloys was started by adding lithium to aluminum-copper, aluminum-magnesium, and aluminum-copper-magnesium alloys. These alloys were chosen to superimpose the precipitation-hardening characteristics of intermetallic Al-Cu-, AlCuMg- and AlMg- precipitates to those of lithium-containing precipitates. Proceeding in this manner, alloys A2020 (Al-Cu-Li-Cd), A1429 (Al-Mg-Li), A2090 (Al-Cu-Li), and A2091 and A8090 (Al-Cu-Mg-Li) evolved. The todays challenges with Al-Li alloy manufacturing and processing are :

- Hot tear susceptibility in the casting process
- High reactivity of Lithium with refractory material, moisture and atmospheric gas
- High scrap rate / high machining costs due to high rejection rate
- Corrosion susceptibility
- Recycling issues
- Al-Li alloys cost 3x as much as conventional Al alloys

Processing Al-Li alloys in the semi-solid state offers high potential to reduce the list of problems. Porosity, volume shrinkage and the hot tear susceptibility may be significantly improved by the lower liquid phase content of 40-60% during the thixoforming process. Machining and overall costs are also reduced because of the possibility to manufacture near-net shape components. This was the reason to start this investigation in 2001 in the framework of Aachens collaborative research centre SFB289.

2 Demands on thixoformable alloys and criteria for alloy selection

In order to obtain excellent processability in the semi-solid state, thixoformable alloys have to meet the following specifications [4,5]:

- Formation of a globulitic solid phase (<150µm grain size) in the semi-solid-interval to support proper laminar flow and die filling
- Low temperature sensitivity of the solid/liquid phase content to enhance the process window of the reheating/holding process prior to the forming procedure
- Rapid reduction of viscosity of the semi-solid slurry under shear stress and laminar flow to obtain low porosity and near-net shaped components

All these requirements are almost fulfilled by the wide spread thixoformable aluminum alloys A356-AlSi7Mg0,3 and A357-AlSi7Mg0,6 and explain their predominantly use in industrial thixoforming processes. Within this research action contribution to the development of thixoformable is made on the basis of a systematic approach from thermochemical calculation to the synthesis and evaluation of Al-Li-X alloys. The investigated alloys are Sc and Zr modifications of the mainly solution hardening AlLi2,1Mg5,5 (A1420) system.

3 Thermochemical calculations

In order to predict important key values for the processability in the semi solid state thermochemical calculations with a slightly modified version of the COST 507 database for light metal alloys [6] was applied using Thermo-Calc© Software Version P. In this database the important ternary systems Al-Cu-Li, Al-Li-Mg and Al-Cu-Mg are included. Generally for ternary and higher order Li-containing systems experimental data are rather rare and contradictory.

Table 1: Relevant properties of the alloy A1420 calculated using the Scheil-Gulliver approximation

	Li	**Mg**	**T_{50},°C**	**df_l/dT**	**T_{50}-T_s**	**Intermetallic phases**
mean	2,1	5,5	603	0,010	145	3,4%
Low	1,9	5,0	610	0,012	152	
High	2,3	6,0	595	0,009	137	

In addition to equilibrium calculations the Scheil-Gulliver approximation was used to simulate the effect of microsegregation on the solidification (**Table 1, Fig. 1 and 2**). In this approximation it is assumed that the diffusion rate is infinite in the liquid phase and zero in the solid phases. The calculation can be realized as a series of equilibrium calculations, without knowledge of diffusion rates or microstructure size parameters. On the other hand, the influence of cooling rate can not be simulated in this way. For aluminum alloys the Scheil-Gulliver approximation has been found to reproduce the actual solidification quite well. In principle, the Scheil-Gulliver approximation is symmetric, so that it simulates the remelting of a solidified microstructure just as well. This only applies for the as cast microstructure. If the material is well homogenized, an equilibrium calculation may reproduce the melting behaviour better.

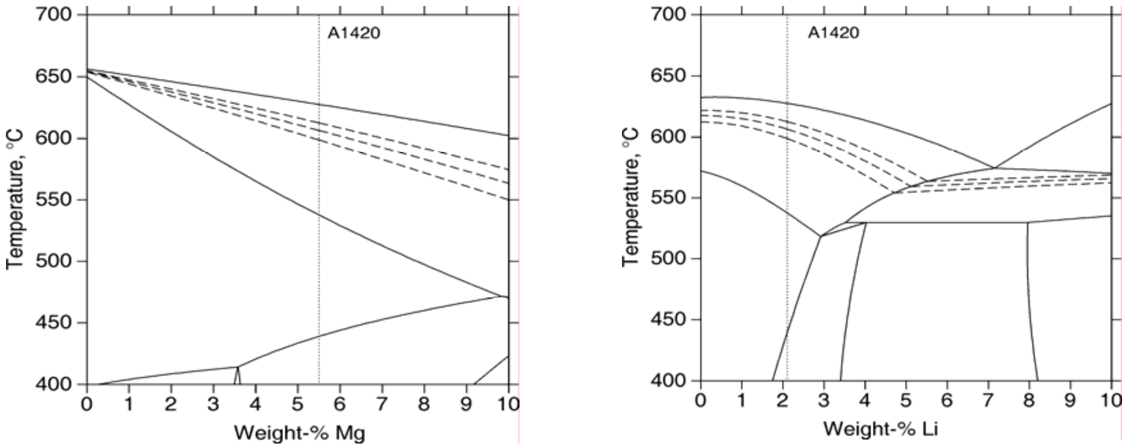


Fig. 1: Calculated isoplethal section at 2,1 weight-% Li (left) and 5,5 weight-% Mg (right)

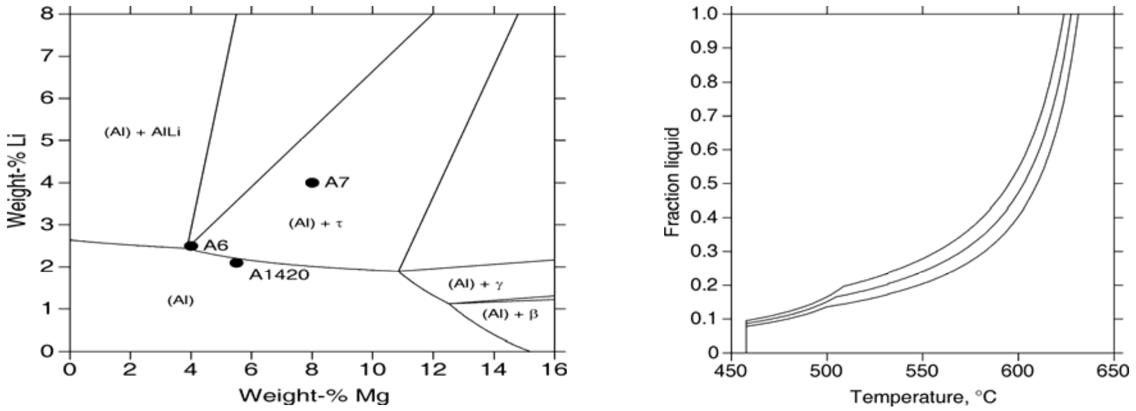


Fig. 2: Calclated isothermal secation at 450°C in the Al-Li-Mg system (left) and calculated solidification curves for AlLi2,1Mg5,5 using Scheil-Gulliver approximation (right)

Experimental investigations on microstructure, intermetallics formation and mechanical properties were conducted to prove if these Al-Li-Mg alloys can fulfil all the demands of a high-quality semi-solid processed component. Therefore the Al-Li-Mg alloys were synthesized with the aid of a “Design of Experiments” model (DoE) to minimize the investigation effort and to maximize reliability of the generated experimental data.

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

On the basis of the well known AlLi2,1Mg5,5 (A1420) Sc and Zr additions in the range of 0-0,3 weight% were added as well as the casting temperature (750-850°C) was varied representing the most important influencing parameters. A total number of 22 billets have been molten and cast (**Table 2**).

Table 2: Applied DoE investigation plan to synthesize Al-Li-Mg-Sc-Zr thixo-alloys

Billet number	Wt% Scandium	Wt% Zirconium	Casting temperature [°C]
N1	0	0	750
N2	0	0	750
N3	0,3	0	750
N4	0,3	0	750
N5	0	0,3	750
N6	0	0,3	750
N7	0,3	0,3	750
N8	0,3	0,3	750
N9	0	0	850
N10	0	0	850
N11	0,3	0	850
N12	0,3	0	850
N13	0	0,3	850
N14	0	0,3	850
N15	0,	0,3	850
N16	0,3	0,3	850
N17	0,15	0,15	800
N18	0,15	0,15	800
N19	0,15	0,15	800
N20	0,15	0,15	800
N21	0,15	0,15	800
N22	0,15	0,15	800

The high reactivity of Lithium with atmospheric gases and refractory material and its high equilibrium vapour pressure makes it necessary to use special melting and casting techniques. A Lithium resistant SiC crucible was installed in a vacuum/overpressure furnace shown in **Fig. 3**. Al-Li billets with different compositions were made from precursor metals and masteralloys as can be seen from **table 3**.

Table 3: Chemical composition of precursor metals and masteralloys

Aluminum 99,999 as ingot

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti
[wt %]	< 0,2	< 0,25	< 0,03	< 0,03	< 0,03	< 0,07	< 0,03

Magnesium 99,8 as ingot

Element	Cu	Mn	Ni	Fe	Si	others	total
[wt %]	< 0,02	< 0,10	< 0,002	< 0,05	< 0,1	< 0,05	< 0,2

Lithium 99,9 as rod

Element	Na	K	Ca	Fe
[wt %]	< 0,9	< 0,05	< 0,04	< 0,01

AlZr10 as ingot

Element	Fe	Zr	Si	others
[wt [%]	< 0,3	9,5-10,5	< 0,3	< 0,05

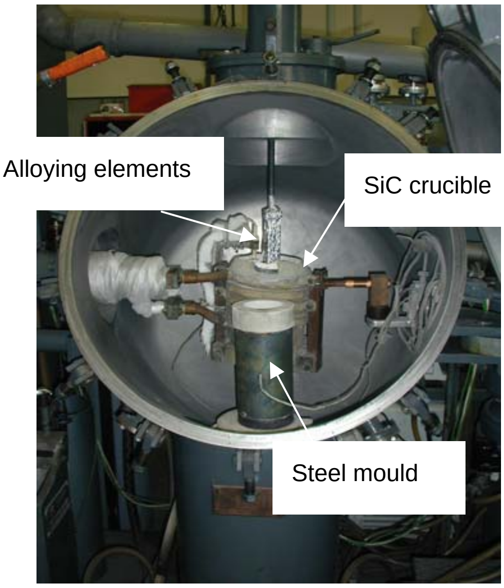
AlSc1,8 as ingot

Element	Fe	Sc	Si	others
[wt %]	< 0,1	1,8	< 0,1	< 0,05

The synthesis of Al-Li-Mg based alloys was conducted according to the following scheme :

- alloying of Al (99,999%) AlZr10 and AlSc1,8 at 850°C in a SiC crucible under air Atmosphere, holding for 10 min.
- evacuation of furnace and filling with Argon (2 times)
- setting furnace under 3,5 bar overpressure
- alloying Li, Mg into the melt at 820°C, holding for 5 min..
- casting into a cold iron 3,5” diameter mould

The total mass of each manufactured billet was approximately 3 kg (see **Fig. 4** right).

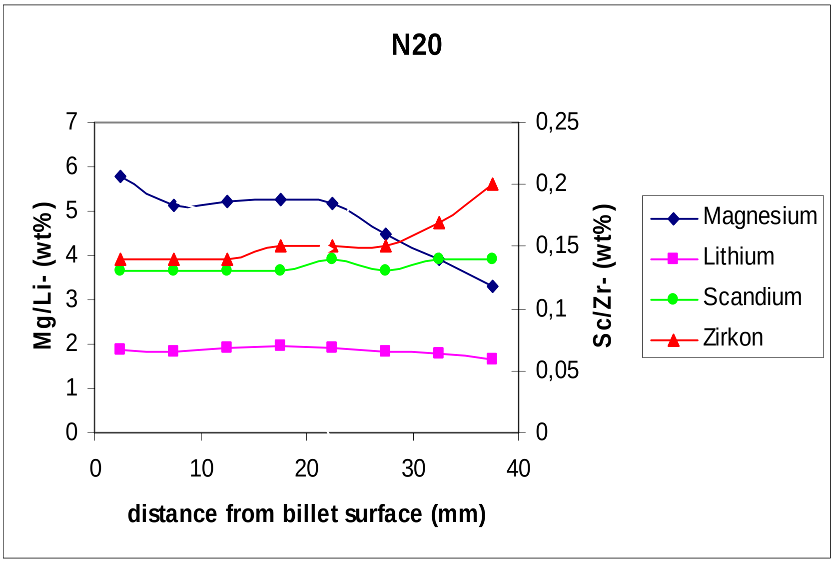


Technical specifications :

- Melting temperature: max. 1600 °C
- Crucible volume: max. 2 l
- Overpressure: max. 3,5 bar
- Vacuum: 2 x 10^{-5} mbar at 20°C
- Frequency: 10 kHz
- Power: max. 50 kW

Fig. 3 : Vacuum/Overpressure furnace **at IME** used for Al-Li-X billet synthesis

Fig. 4 illustrates exemplary the results of the chemical element distribution analysis with the aid of ICP (Inductive Coupled Plasma) of AlLi2,1Mg5,5Sc0,15Zr0,15 (billet N20). This chemical analysis outlines element segregation effects in radial direction of the billet, which has to be taken into consideration for the following investigations. This phenomena occurs in continuous casting processes of alloys with wide solidification interval and is known as „inverse segregation“. Similar chemical segregation effects occurred in all investigated Al-Li-Mg billets.



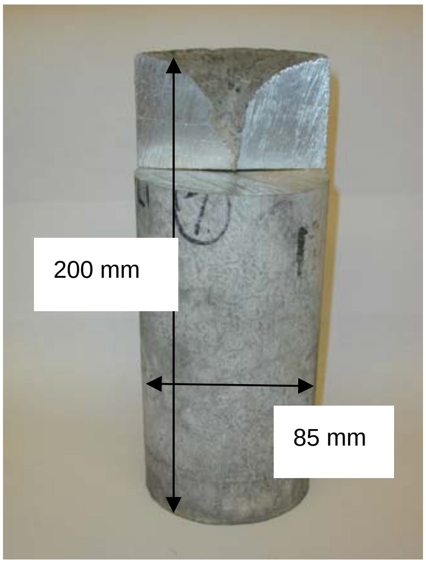


Fig. 4 : Element distribution [wt%] in a AlLi2,1Mg5,5Sc_xZr_y billet, Li and Mg left axis, Sc and Zr right axis (left); Al-Li-Mg billet (right)

5 DoE Results on microstructure

As shown in **Fig. 5** Scandium and Zirconium additions generally resulted in a strong grain refining effect on the microstructure of the investigated AlLi2,1Mg5,5 alloy in the as cast condition. As can be seen, the average grain size decreases from >>500µm to approx. 30µm when Scandium and Zirconium is added. This material should be an excellent precursor for subsequent reheating into the semi solid state and semi solid processing.

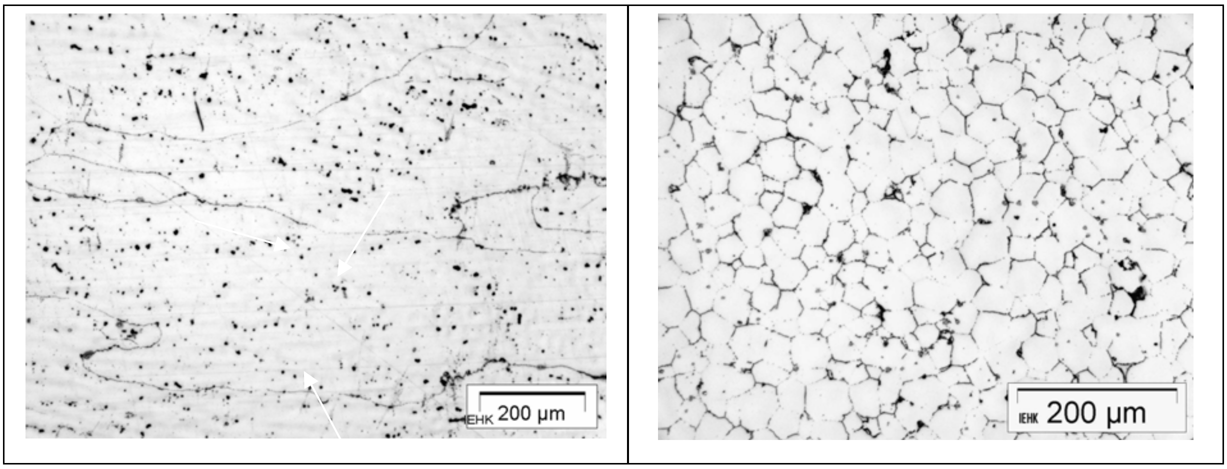


Fig. 5 : Effect of Sc,Zr addition on grain size and microstructure of AlLi2,1Mg5,5Sc_x Zr_y (billet N1 0%Sc and 0%Zr left, billet N17 0,15%Sc and 0,15%Zr right)

The strongest effects on grain size were observed when both elements (Sc and Zr) were added to the matrix, shown in **Fig. 6** as a statistical evaluation result from software Modde®. With an preset confidence level of 95% a significant influence of Zr and Sc additions is detected. This can be stated as the width of the confidence interval (thin bar) does not exceed the width of the effects bar (thick bar). On the other hand there is no significant influence of casting temperature (Gie) and its mixture with Sc resp. Zr addition on the mean grain size.

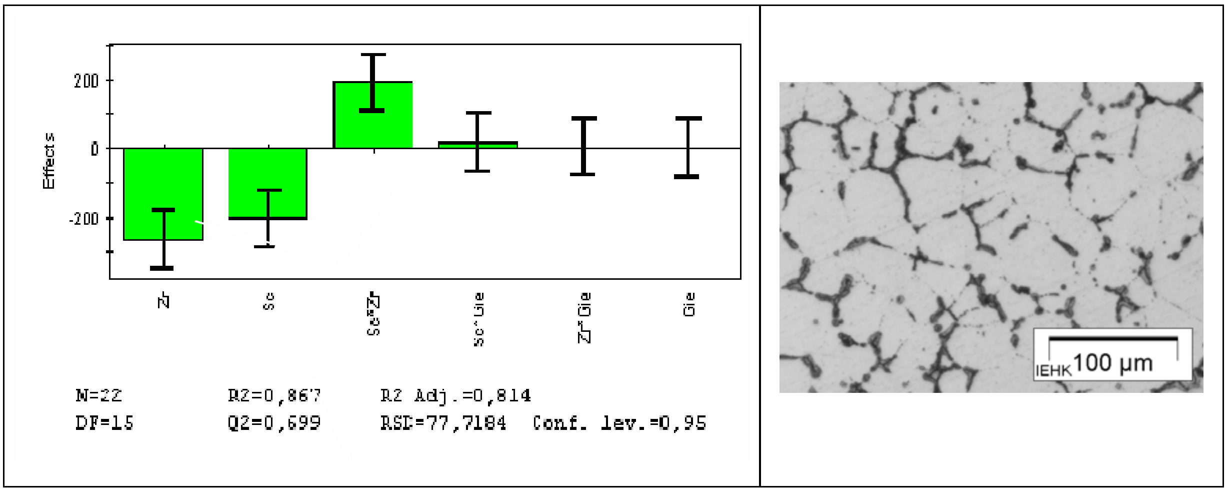


Fig. 6 : Statistical effects of Sc and Zr addition (single and mix) and casting temperature (Gie) on grain size of AlLi2,1Mg5,5ScZr (left), microstructure of billet N17 (right)

As shown in **Fig. 7** there is a quite good relationship between Sc- and Zr-content on the final grain size. No significant impact of the casting temperature on the resulting grain size can be seen and therefore the processing window for the precursor casting process is enlarged. These results confirm that Scandium has the strongest grain refining effects on aluminium alloys. Zirconium was added to further enhancement of mechanical properties. Further important microstructure evaluation figures e.g. shape factor and contiguity will be investigated in the ongoing research work as well as reheating experiments to analyse the materials microstructure evolution within the semi solid state.

Investigation: Al-Li-Mg-Sc-Zr (PLS, comp.=5), 4D Contour of Grain Size

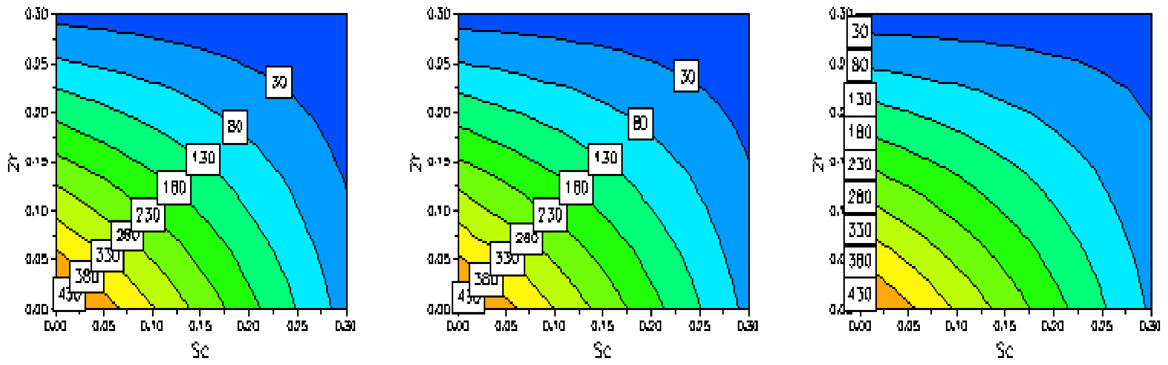


Fig. 7 : 4D Contour plot of Grain Size (µm) for three different casting temperatures (left: 750°C, middle: 800°C, right: 850°C)

6 Mechanical properties

In order to pre-evaluate the material static tensile tests were carried out. As depicted in **Fig. 8** (left) specimens were desected from the top, middle and bottom section of the synthezised Al-Li-Mg billets. The static properties (**Fig. 8** right) already in the as cast condition are compareable to conventional AlSi7Mg0,3 semi-solid standard alloy in a T6 heat treated condition (TS~260MPa, UTS~310MPa, A~7%). Therefore further potential in improving mechanical properties can be expected after heat treatment of the manufactured Al-Li-Mg precursor material.

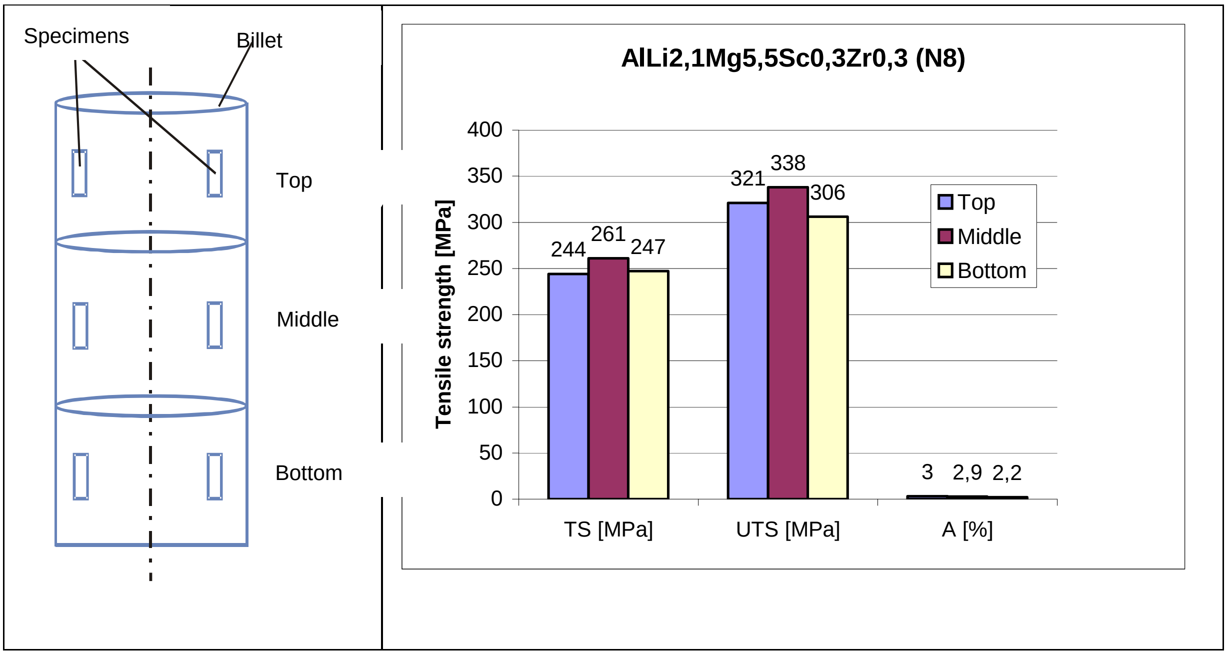


Fig. 8 : Mechanical properties of synthesized AlLi2,1Mg5,5Sc0,3Zr0,3 (billet N8) in the as cast condition

This effect gets even more significant, if the true densities are respected in **Table 4**.

Table 4: Comparison of strength to weight ratios

	AlSi7Mg0.3 (T6)	**AlLi2,1Mg5,5Sc0,3Zr0,3 (as cast)**
Density [g/ccm]	2,65	2,43
TS/ρ	96	113
UTS/ρ	115	181

7 Assessment and outlook

Processing AL-Li alloys in the semi-solid state can offer a variety of improvements for this type of alloys. State of the art Al-Li alloys are generally wrought alloys which are processed by rolling, extrusion and forging. Specific Al-Li casting alloys which offer a high degree in freedom of shape are still not available for a wide spread commercial use. Challenges that have to be addressed for Al-Li alloys are their high reactivity, hot tear susceptability, occurrence of brittle intermetallic phases, chemical corrosion recycability and high material and processing costs. Due to the reduced liquid phase content compared to conventional fully liquid casting, it is possible to remove some of the problems occurring with conventional processing of Al-Li alloys [7]. This technology may substitute state of the art castings and forgings in automotive applications by SSM processed Al-Li alloys (**Fig. 9**).

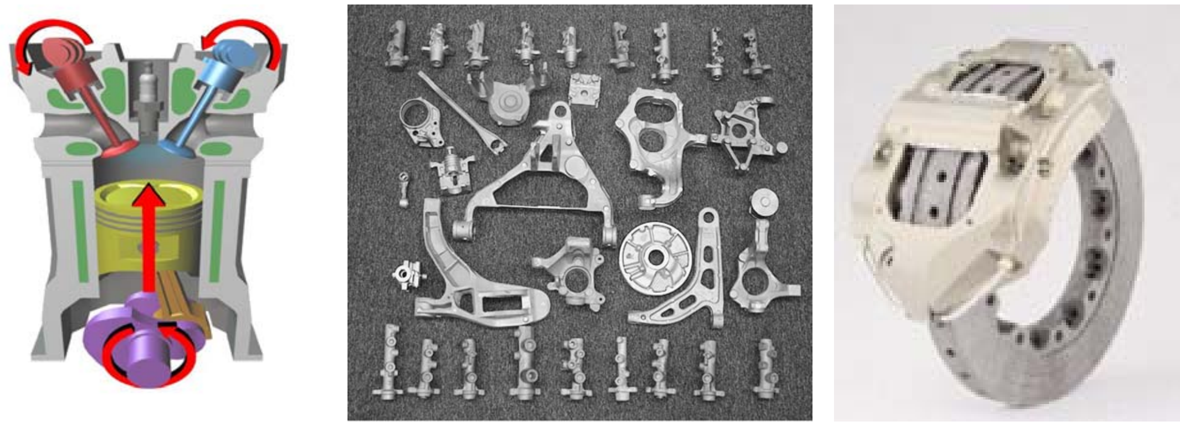


Fig. 9 : SSM Al-Li future application in high performance engine (left), as substitution for typical automotive casting (middle) and race caliper (right)

Thermochemical calculations did help to identify suitable alloy systems. With the aid of chemical grain refining (Sc and Zr) it was possible to manufacture a suitable Al-Li-Mg precursor material with a fine and globular grain structure and promising mechanical properties. Future developments will focus on first AlLiMg prototypes processed by SSM to evaluate the feasibility of this new processing route for this high performance alloys.

8 Acknowledgements

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG), which supports this work in the frame of a collaborative research center (SFB 289). We also thank our partner institute in Aachen IEHK for mechanical testing and microstructure evaluation.

References

[1] Spencer, D. B., Mehrabian, R., Flemings, M. C., 1972, The Rheological Behaviour of Sn-15Pb in the Crystallization Range, Metall. Trans., 3, 1925

[2] Joly, P. A., Mehrabian, R., 1976, The rheology of a Partially Solid Alloy, J. Mater. Sci., 11

[3] Flemings, M. C., 1977, Proc. Japan-US Joint Seminar on Solidification of Metals and Alloys, 1

[4] Kopp, R., Kallweit, J., Möller, T. Neudenberger, D., 2001 Different Forming Technologies for Aluminum and Steel in the Semi-Solid State, Production Engineering Vol. VIII/1, German Academic Society for Production Engineering

[5] Uggowitzer, P. J., Gullo, G.-C., Wahlen, A., 2000 Metallkundliche Aspekte bei der semi-solid Formgebung von Leichtmetallen, Proceedings of the 1st Ranshofener Leichmetalltage, ed.: Kaufmann, H. Uggowitzer, P. J.

[6] I. Ansara, A.T. Dinsdale and M.H. Rand (Eds.), Thermochemical Database for Light Metal Alloys (Volume 2), COST 507 Final Report Round 2, European Communities, Luxembourg, 1998.

[7] R. Sauermann, P. J. Uggowitzer, W. Bleck, et. al., Aluminum-Lithium alloy development for thixoforming, Z. Metallkd. 95 (2004) 12, Carl Hanser Verlag, München, p. 1097-1107