R. Sauermann, B. Friedrich[1]; W. Püttgen, W. Bleck[2]; E. Balitchev, B. Hallstedt, J.M. Schneider[3]; H. Bramann, A.Bührig-Polaczek[4]; P. J. Uggowitzer[5]

[1] IME Process Metallurgy and Metal Recycling, RWTH Aachen University
[2] IEHK Institute for Ferrous Metallurgy, RWTH Aachen University
[3] MCh Materials Chemistry, RWTH Aachen University
[4] GI Foundry Institute, RWTH Aachen University
[5] ETH Zürich, Metal Physics and Technology

Aluminum-Lithium Alloy Development for Thixoforming

This paper presents a scientific contribution to the development of light weight / high performance Aluminum-Lithium alloys suitable for semi-solid processing. Thermodynamic calculations identified the most promising compositions with focus on solidus liquidus interval, fraction solid versus temperature and phase reactions. The synthesis of Al-Li precursor billets was performed by overpressure induction melting in controlled atmosphere. DTA and microstructure investigations on Al-Li specimens were carried out as well as Thixocasting trials of demonstrator components. New Rheocasting (NRC) of Al-Li alloys was investigated to identify the potential of this alternative precursor material route. It is shown that specifically developed Al-Li alloys offer great potential for semi-solid manufacturing.

Keywords: Thixoforming, New Rheocasting, alloy development, Aluminum-Lithium

1 Introduction

A scientific group of the RWTH Aachen University have been investigated the technological aspects of semi solid processing of metals within the scope of a 9 year collaborative research action (SFB 289). Semi solid technology is defined by a processing of metals in the semi solid 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 volume.

"Thixocasting" and "Thixoforging" are currently the two metal shaping methods where the characteristics of semi solid metal slurries are exploited. Compared to conventional die casting the following advantages of semi-solid forming are known:

- Thick/thin walled structures can be produced
- Cast and wrought alloys can be used
- Homogeneous microstructures are obtained leading to homogeneous properties
- Pressure-tightness is improved
- Heat treatment is applicable

Besides conventional Thixocasting (CTC) there are also alternative processing routes using the „Slug on demand“ technology such as New Rheocasting (NRC), which help to reduce production costs and allow inhouse recycling [6].

Today industrialized thixoforming alloys are conventional cast or wrought alloys which have not been specifically adapted for the requirements of semi solid processing. Such an alloy development has only been partially performed yet and is limited to only slight modifications of standard wrought or cast alloys [4,5]. This work describes methods and investigations on Aluminum-Lithium alloy development for thixoforming and gives examples for application and process orientated alloy development.

Aluminum-Lithium alloys (Al-Li) are already used in high-tech industrial applications. Especially Al-Li wrought alloys e.g. AA8090 and AA2091 are fabricated as extruded profiles or rolled sheets for aero and spacecraft applications. Also drop-forged components e.g. Al-Li racecar calipers demonstrate the range of possible application areas for Aluminum-Lithium alloys (**Fig. 1**). Their low density, high specific strength and high elastic modulus make them well suited for a number of high performance applications. Unfortunally there is no wide spread use of Aluminum-Lithium alloys due to their high material costs and complex as well as sensitive processing, although significant research work is known [7]. This work presents a method how to develop Al-Li Thixoalloys on a systematically and fundamentally based procedure.

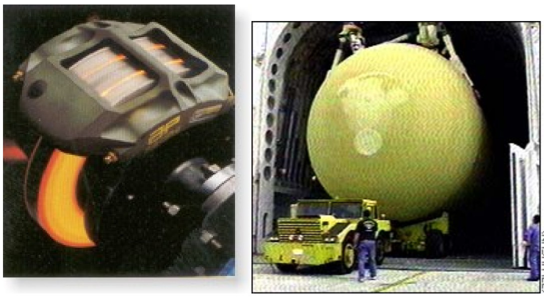


Fig. 1 : Formula one Al-Li Monobloc-caliper (left – AP Racing) and Al-Li space shuttle fuel tank (right - NASA)

The 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
- Corrosion susceptibility
- Recycling

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 susceptability may be significantly improved by the lower liquid phase content of 40-60% during the thixoforming process. Machining costs are also reduced because of the possibility to manufacture near-net shape components.

2 Requirements on thixoformable alloys and alloy selection

In order to obtain excellent processability in the semi-solid state, thixoformable alloys have to meet the following specifications [8,9]:

- Formation of globulitic solid phase (<150µm grain size) in the semi-solid-interval to support proper laminar flow and die filling
- Low temperature sensitivity of solid/liquid phase content to enhance the process window of the reheating process prior to the forming process
- Minimum temperature range of 10K vs. 40-60% liquid phase to define the process window of reheating
- 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 fulfilled by the most wide spread thixoformable aluminum alloys A356-AlSi7Mg0,3 and A357-AlSi7Mg0,6 and explain their extensive use in industrial thixoforming processes. Within this research campaign the listed criterias were applied to identify suitable Al-Li alloy systems for semi-solid processing. The investigated alloys are modifications of the precipitation hardening Al-Li-Cu system and the mainly solution hardening Al-Li-Mg system. For comparison AA8090 and AA2090 where also taken into consideration (**Table 1**).

3 Thermodynamic calculation

For thermodynamic calculations a slightly modified version of the COST 507 database for light metal alloys [10] was used. In this database the important ternary systems Al-Cu-Li, Al-Li-Mg and Al-Cu-Mg are included, but not the quaternary Al-Cu-Li-Mg system. This system was simply extrapolated from the lower order systems. Generally for ternary and higher order Li-containing systems experimental data are rather scarce and contradictory. The systems are also fairly complex, containing several intermetallic phases. Phases encountered in the present calculations, i.e. in the Al-rich corner, are T_1 (Al_2CuLi), T_2 (Al_6CuLi_3, quasicrystalline), T_B ($Al_{7.5}Cu_4Li$), θ (Al_2Cu), AlLi (dissolves Mg), τ (Al_2LiMg), γ ($Al_{12}Mg_{17}$, dissolves Li) and β (Al_8Mg_5). In Al-Cu-Li-Mg alloys a bcc phase with the approximate composition $Al_5Cu(Li,Mg)_3$ is often found [11-13]. This phase appears to form a continuous solid solution from the Al-Cu-Li system, where it is known as R-phase, to the Al-Cu-Mg system, where it is known as τ (not the same τ as Al_2LiMg). The quasicrystalline T_2 phase, which is very close to the R-phase in composition (and local atomic environment) also dissolves Mg, but becomes metastable above a certain Mg-content. It forms metastably in the Al-Cu-Mg system at very high cooling rates [12]. At least one quaternary phase has been identified as well [11,14]. These solid solutions and quaternary phases have not yet been included in the database. For precipitation hardening purposes, the phases Al_3Li (δ′, metastable in the Al-Li system) and S (Al_2CuMg) have been suggested [15].

In addition to equilibrium calculations the Scheil-Gulliver approximation was used to simulate the effect of microsegregation on the solidification. 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, though. If the material is well homogenized, an equilibrium calculation may reproduce the melting behaviour better.

One part of the alloy selection is based on the commercial alloy AA2090, which is a wrought Al-Cu-Li alloy. This alloy has a rather large solidification interval and a steep solidification curve around 50% liquid phase (f_L=0.5) expressed as df_L/dT. By increasing the amount of alloying elements, i.e. by going in the direction of a cast alloy, the thixoforming properties can be improved at the expense of formation of more intermetallic phases, which could lead to embrittlement. In the second part we looked closer at two Al-Li-Mg alloys due to their light weight potential as well as the commercial AA8090 alloy (Al-Cu-Li-Mg) as a "bridge" between both alloy systems. An isothermal section of the Al-Cu-Li system at 520°C with the investigated alloys included is shown in **Fig. 2**.

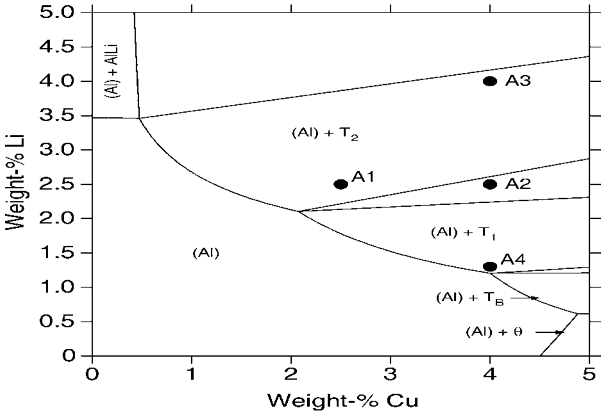


Fig. 2: Calculated isothermal section of the Al-Cu-Li system at 520°C and locations of the four Al-Cu-Li alloys investigated in this study

This is just below the temperature where the last liquid in equilibrium with fcc-(Al) has disappeared. An isoplethal section at 4.0 weight-% Cu is shown in **Fig. 3** (left). Solidification curves of the four Al-Cu-Li alloys using the Scheil-Gulliver approximation are shown in **Fig. 3** (right). Note that alloy A3 shows a very large amount of eutectic solidification (more than 30%).

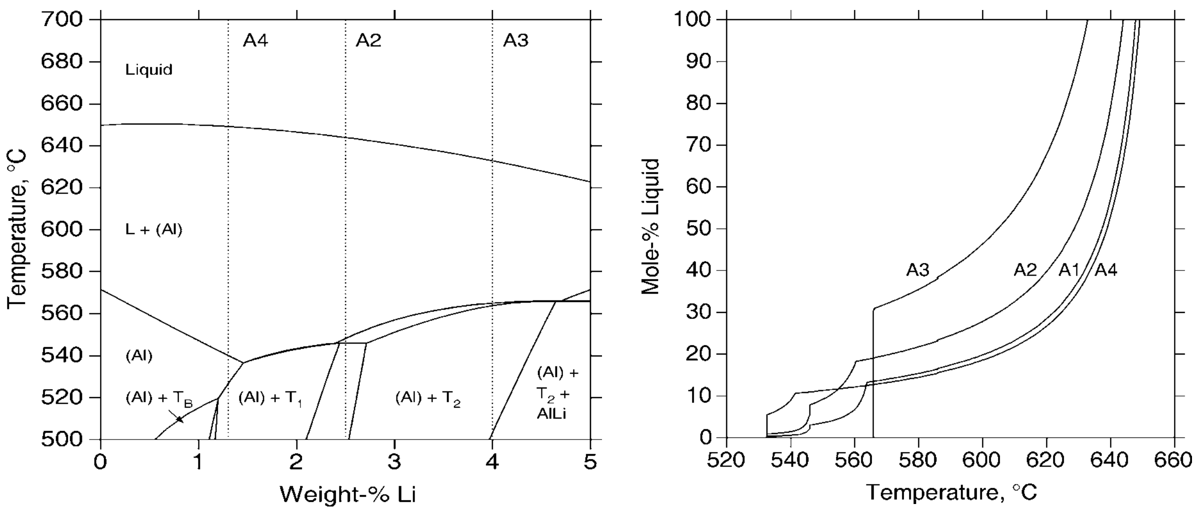


Fig. 3: Calculated isoplethal section at 4.0 weight-% Cu and locations of the three Al-Cu4-Lix alloys investigated in this study (left). Calculated solidification curves for alloys A1 to A4 using the Scheil-Gulliver approximation (right)

The two investigated Al-Li-Mg alloys are indicated in the isothermal section at 450°C in **Fig. 4**.

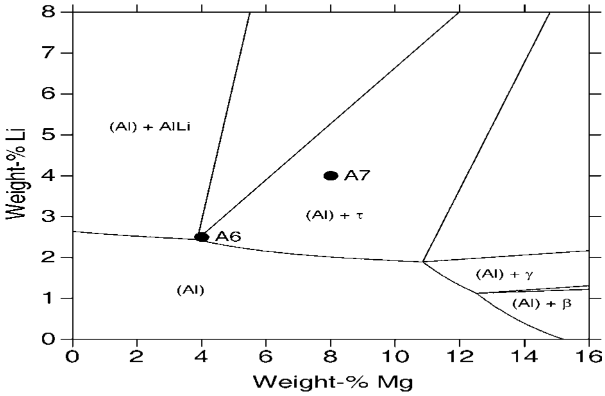


Fig. 4: Calculated isothermal section at 450°C in the Al-Li-Mg system

Relevant thixoforming properties, calculated using the Scheil-Gulliver approximation, for the considered alloys are summarized in **Table 1**. Compositions are given in weight-% and phase fractions are given as molar fractions, which are close to volume fractions. T_{50} is the temperature where 50% liquid is present, df_L/dT is the slope of the solidification curve at 50% liquid and $T_{50}-T_s$ is the temperature interval between 50% liquid and complete solidification. The absolute accuracy of the temperatures given is not expected to be better than ±10 K, so that they cannot be directly used to regulate the process. For good thixoforming properties df_L/dT should be small and $T_{50}-T_s$ should not be too large to avoid hot tearing. Liu et al. [16] suggest that df_L/dT should be less than 0.015 and that $T_{50}-T_s$ should be less than 150 K to assure good processability. For e.g. alloy A1 the temperature window between 40 and 60% liquid is about 9 K, which could be too small to allow reproducible processing. The Alloys A5 and A6 have very large solidification intervals, possibly leading to hot tearing problems. The Alloys A3 and A7 form excessive amounts of intermetallic phases, possibly leading to embrittlement. Alloy A2 could represent a reasonable compromise between processability and final properties.

Table 1: Summary of relevant properties of considered alloys calculated using the Scheil-Gulliver approximation

Alloy	**Cu**	**Li**	**Mg**	**T_{50}, °C**	**df_L/dT**	**$T_{50}-T_s$**	**expected amount of intermetallic phases**
A1(AA2090)	2.5	2.5	–	637	0.023	105	4.7% T_2, 1% T_1
A2	4.0	2.5	–	629	0.015	97	4.8% T_2, 2.7%T_1, 0.3% T_B
A3	4.0	4.0	–	605	0.0083	39	12.5% T_2, 0.6% AlLi
A4	4.0	1.3	–	639	0.024	107	2.5% T_1, 2.1% T_B
A5 (AA8090)	1.2	2.5	0.7	638	0.026	197*	3.3%T_2, 0.5% AlLi, 0.4% τ
A6	–	2.5	4.0	613	0.012	155	5.2% τ, 2.7% γ
A7	–	4.0	8.0	542	0.0044	84	15.5% τ, 5.9% γ, 1.1% AlLi

* Less than 2% liquid below 507°C

Experimental investigations on rheology, microstructure, intermetallics formation, mechanical and corrosion properties have to prove if these Al-Li alloys can fulfill all the demands of a high-quality semi-solid processed component. Therefore the seven Al-Li alloys were synthesized.

4 Synthesis of Al-Li precursor material

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, Fig.5 (left). The Al-Li billets with different compositions were metallurgically synthesized directly from precursor metals and masteralloys, Table 2.

Table 2: Chemical composition of precursor metals and masteralloys

Aluminum 99,7

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

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

Lithium 99,0

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

AlZr10

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

AlTi5B1

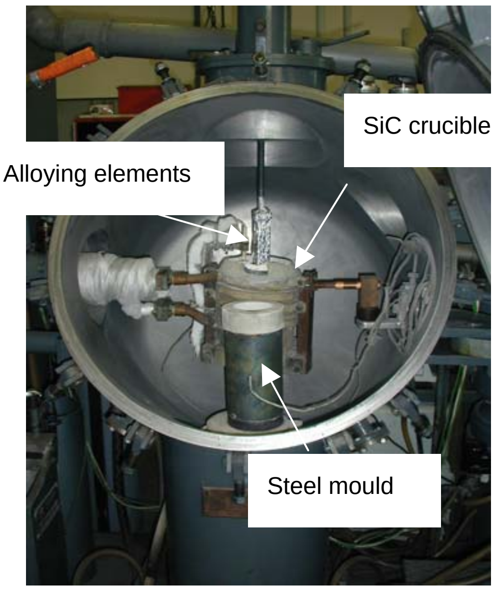
Element	Fe	Si	Ti	B	others
wt [%]	< 0,3	< 0,3	4,5-5,5	0,9 - 1,1	< 0,05

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

- alloying of Al (99,8%) and Cu (99,99%) at 850°C in a SiC crucible, holding for 10 min.
- Evacuation of furnace and filling with Argon (2 times)
- setting furnace under 3,5 bar over-pressure
- alloying Li, Mg into the Al-Cu melt at 820°C, holding for 5 min.
- alloying AlTi5B1 grain refiner at 820°C, holding 5 min.
- casting into a cold iron 3,5" diameter mould

Total mass of each manufactured billet was approximately 3 kg (**Fig. 5** right).

Preliminary casting experiments without the aid of chemical grain refining resulted in extensive dendritic grain growth and grain size beyond 1000µm. Therefore 0,2wt% Ti as $AlTi_5B_1$ masteralloy was added to the Al-Li alloys which led to satisfactory results with regard to grain size and grain morphology, as explained later.



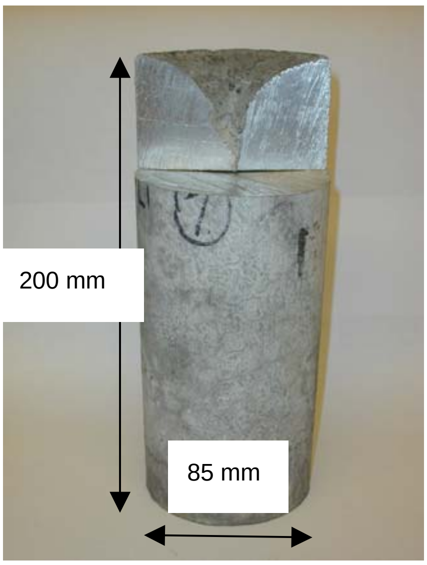


Fig. 5 : Vacuum/Overpressure furnace (left) Al-Li billet (right)

Fig. 6 illustrates exemplary the results of the chemical element distribution analysis with the aid of ICP (Inductive Coupled Plasma) on the AlLi4Mg8Ti0,2 (Nr. A7) billet. This chemical analysis outlines element segregation effects in radial direction of the billet, which has to be taken into consideration for the following investigations. Similar chemical segregation effects occurred in all investigated Al-Li billets.

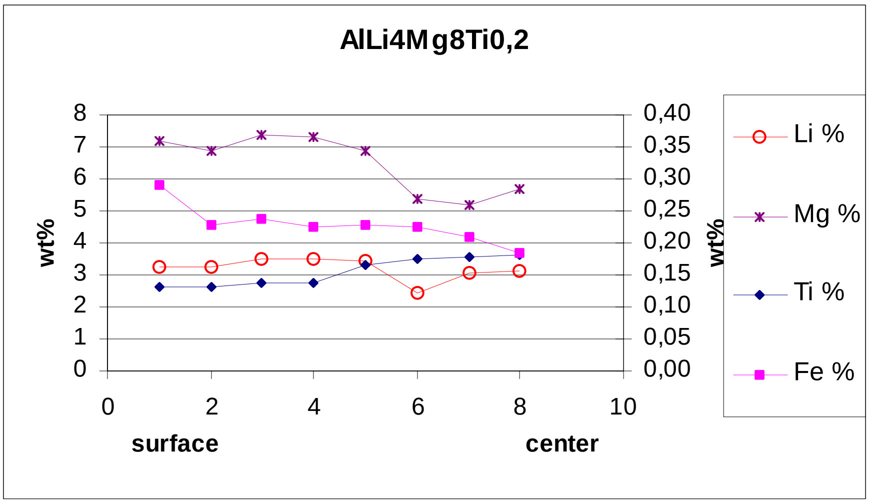


Fig. 6 : Element concentration distribution [wt%] in AlLi4Mg8Ti0,2 billet, Li and Mg left axis, Ti and Fe right axis

5 Differential Thermal Analysis measurements

Thixoforming requires a specific amount of fraction liquid, which has to be adjusted by an accurate temperature control. A small slope of the f_L=f(T)-function is considered to be beneficial for the process stability. Differential Thermal Analysis is applied to measure the temperature difference between the sample to be investigated and a reference sample as a function of temperature or time. The samples are subjected to the same temperature program. The associated German standard is the DIN 51007. The measurement is very sensitive to many influencing factors, which have to be considered in order to minimize the total error of this kind of measurement. The measurements are generally influenced by a lot of factors so that the resulting total uncertainty could not be reduced to less than 2%. DTA measurements can be used to investigate the applicability of a material for processing in the semi-solid state. The determination of the relevant parameters described in this paper were performed with a DTA-tool from Netzsch-Gerätebau/Selb of the type DTA 404S. This device has the ability to determine a temperature range from room temperature to 1550°C with heating or cooling rates between 0.5 and 50 K/min.

To avoid oxidation of the specimens, the tests are performed with a constant argon flow. The reference substrate is Al_2O_3, which shows no transformation in the temperature range of interest. The weight of the investigated samples is around 200 mg. This amount has been found to be ideal, because the whole bottom of the crucible must be covered with metal in the liquid state. Only in this way is it possible to achieve the relevant accuracy, which is required when determining the difference in temperature between the sample and the reference substrate.

The fraction liquid content, which is dependent on temperature, is calculated with the Proteus-software®, which is a special software for this kind of analysis. The liquid phase content is determined by the application of a peak-partial-area integration. The whole area under the enthalpy curve is used to determine the melting enthalpy of the material, which is equivalent to 100% liquid phase. Regarding the output signal type, a correction of the temperature measurement signal is necessary to take into account the thermal resistance, as described in [17]. In order to analyze the influence of the element segregation within a billet on the fraction liquid content, small samples with a certain distance to each other were cut out in radial direction. The subsequent DTA-tests reveal the influence of the different elements on the semi-solid interval.

Al-Li-Cu

The determined fraction liquid curves of a grain refined and a not grain refined AlLiCu-billet for a heating rate of 10K/min are displayed in **Fig. 8**. The corresponding chemical compositions are given in **Table 3**. The targeted composition of these billets was 4% Li and 4% Cu. The Cu-content at the edge of the billets is roughly one mass-% higher than in the center of the billets whereas the difference in the Li-content is about 0,3%.

The fraction liquid curves of the grain refined and not grain refined condition are similar when considering the accuracy of the measuring method and small deviations of the local chemical composition. The maximum difference of the fraction liquid content in the center of the billet compared to the surface of the billet is 13% at 630°C. It can be concluded, that this small difference in temperature is of advantage for the heating of the billet. Regarding the process window this material exhibits a $T^{10\text{-}25\%}$-interval of 11K (surface of the billet) respectively 19K (center of the billet) and a $T^{40\text{-}60\%}$-interval of 16K for surface and center of the billet.

Table 3: Chemical composition [wt%] of the different regions of the billet for the not grain refined material (left) and the grain refined material (right); „s“=surface, „c“=center

Sample	%Li	%Cu	%Fe
A3-s	3,70	4,10	1,77
A3-c	3,46	3,08	1,02

Sample	%Li	%Cu	%Ti	%Zr	%Fe
A3-s	3,81	4,14	0,15	0,088	0,21
A3-c	3,49	3,18	0,18	0,10	0,17

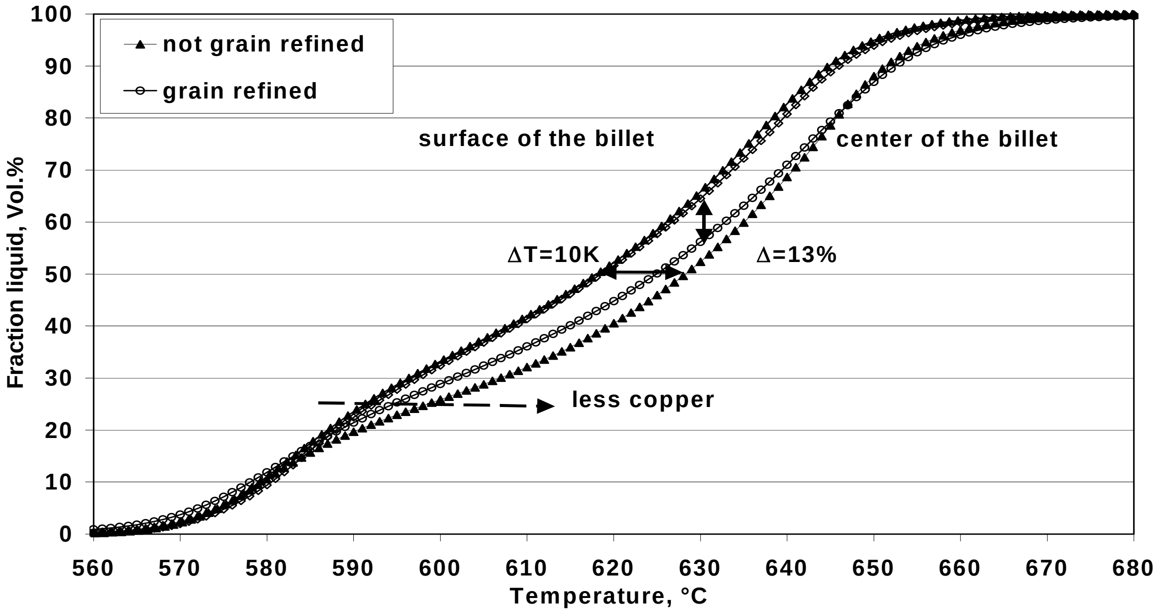


Fig. 8 : Fraction liquid content of the AlLiCu-billets (A3) for a heating rate of 10K/min

Al-Li-Mg

The determined fraction liquid curves for a heating rate of 10K/min for a not grain refined and a grain refined AlLiMg-billet along the radius are displayed in **Fig. 9** and **Fig. 10**. The corresponding chemical compositions are shown in **Table 4.** The targeted compositions of these billets were 4% Li and 8% Mg (A7). The chemical analysis of the billets shows that the Mg-content of the not grain refined material is much higher than for the grain refined billet, which makes a detailed investigation of the influence of the grain refining elements difficult. However it can be assumed, that the addition of small amounts of the grain refiner has an insignificant influence on the fraction liquid as for the investigated for the Al-Li-Cu alloys. The different magnesium and iron contents as a result of segregation have a stronger influence. Higher iron and magnesium contents lead to higher fraction liquid contents at the same temperature. For a fraction liquid content of 50% for the not grain refined material the temperature difference is more than 35K (center of billet = 591°C, surface of billet = 555°C).

Regarding the process window the not grain refined material and the grain refined material have similar $T^{10\text{-}25\%}$ and $T^{40\text{-}60\%}$-intervals with 20K along the whole billet-radius. For billets with an equal targeted composition it can be concluded, that the difference in the real chemical composition regarding the Li- and Mg-content, has a significant influence on the melting interval of the billets. This has to be taken into consideration during the heating of the billets.

Table 4: Chemical composition [wt%] of the different regions of the billet for the not grain refined material (left) and the grain refined material (right)

Sample	%Li	%Mg	%Fe
A7-1	4,03	8,43	0,63
A7-4	4,07	8,66	0,20
A7-8	3,71	7,01	0,08

Sample	%Li	%Mg	%Ti	%Zr	%Fe
A7-3	3,52	7,39	0,14	0,094	0,24
A7-5	3,44	6,89	0,17	0,11	0,23
A7-7	3,15	5,70	0,18	0,13	0,19
A7-8	3,04	5,20	0,18	0,13	0,21

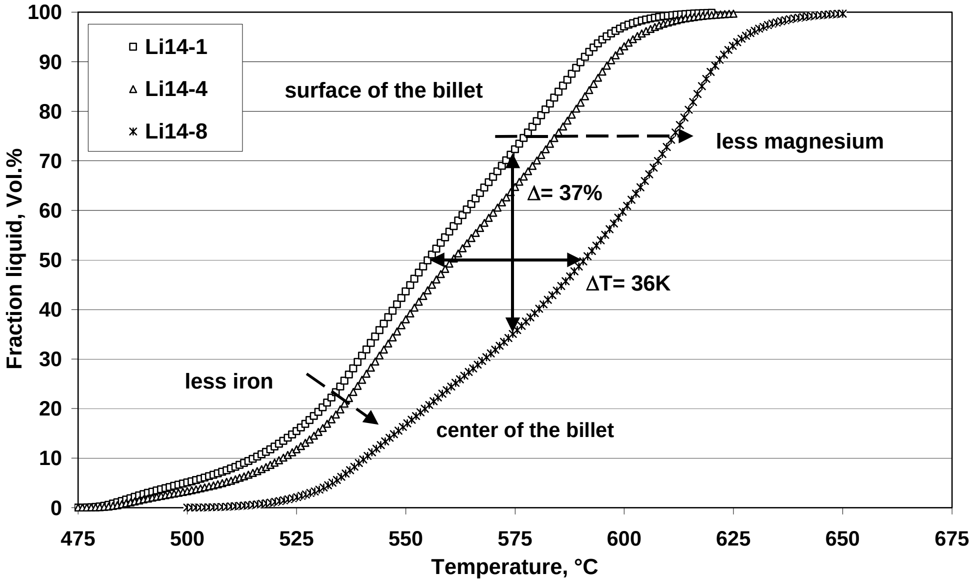


Fig. 9 : Fraction liquid content of the not grain refined AlLiMg-billet (A7) for a heating rate of 10K/min

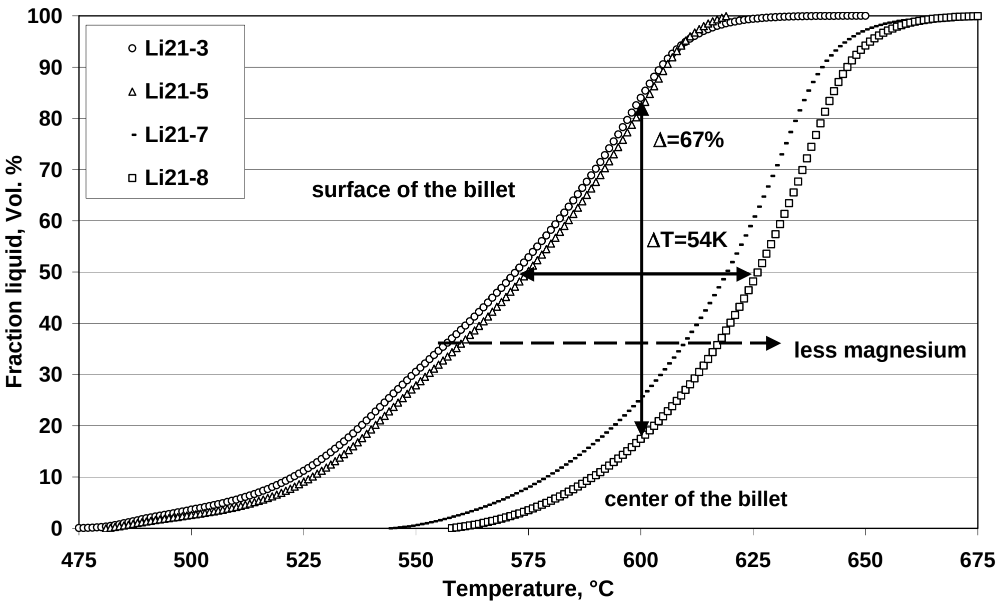
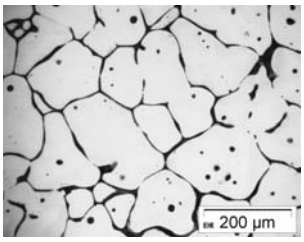


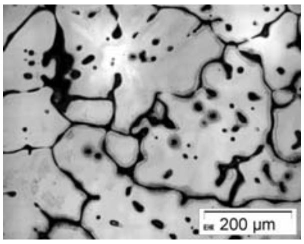
Fig. 10 : Fraction liquid content of the grain refined AlLiMg-billet (A7) for a heating rate of 10K/min

6 Reheating experiments – evolution of microstructure

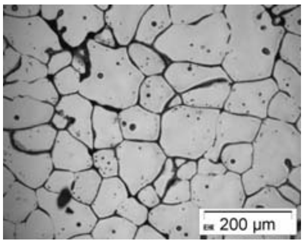
Besides the slope of the f_L=f(T)-function the formation of a globulitic microstructure is very important for the successful thixoforming of the materials. In order to achieve good material-flow the formation of a globulitic solid phase with an average grain size smaller than 150 µm is required. Therefore quenching experiments have been performed. Small samples with a diameter of 4,8mm and a height of 0,7mm have been heated to certain temperatures in the semi-solid interval for different holding times, before quenching in a salt bath. The microstructures of the seven grain refined compositions are displayed in **Fig. 11** for a quenching temperature of 580°C (except AlLi4Mg8 : 500°C) and a holding time of 120s**.** It can be concluded that all investigated materials create a globulitc microstructure with AlLi4Cu4 and AlLi4Mg8 as the best performing alloys.



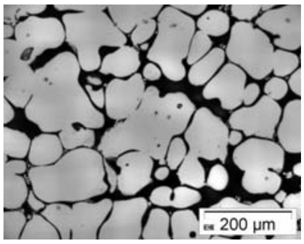
(AA2091) 580°C/120s
*D=116µm /**FF=0,42



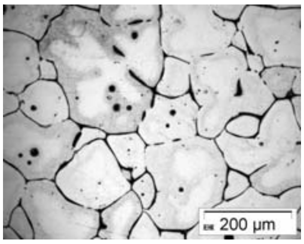
(AlLi2,5Cu4)
580°C/120s D=137µm / FF=0,4



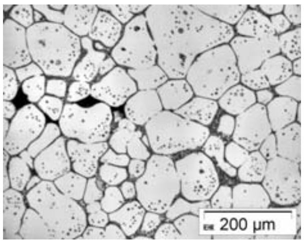
(AlLi1,5Cu4) 580°C/120s
D=107µm / FF=0,39



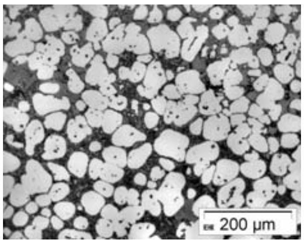
(AlLi4Cu4) 580°C/120s
D=82µm / FF=0,67



(AA8090) 580°C/120s
D=130µm / FF=0,43



(AlLi2,5Mg4) 580°C/120s
D=83µm / FF=0,38



(AlLi4Mg8) 500°C/120s
D=52µm / FF=0,4

Fig. 11 : Al-Li-X microstructure after quenching from the semi-solid interval with grain refiner; * D=mean grain size, **FF=Formfactor (0=dendritic, 1=full spherical)

7 New Rheocasting experiments - evolution of microstructure

Parallel investigations on the possibilities of applying the New Rheo casting (NRC) process on Al-Li-X alloys were conducted. The NRC route is based on the primary solidification of the solid phase during cooling from a temperature slightly above the liquidus temperature (10-50°K) of the alloy **Fig. 12**. When the process parameters (undercooling rate, mould design etc.) are correctly chosen it is possible to suppress dendritic grain growth and to obtain a globulitic slurry for subsequent semi-solid processing. This should also happen without the aid of grain refining elements like Titan.

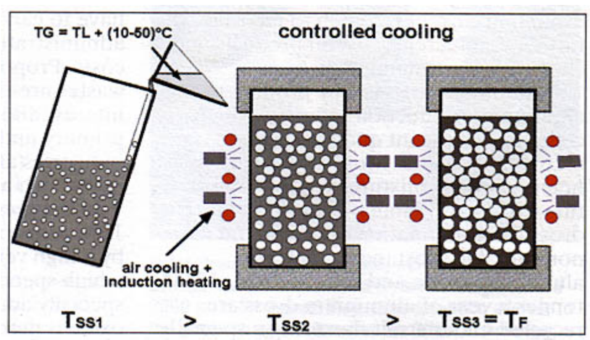


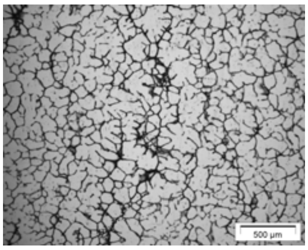
Fig. 12 : NRC process scheme [P. J. Uggowitzer – ETH Zürich]

The synthesis of the seven Al-Li based slurries with the aid of the New Rheocasting process was conducted according to the following scheme :

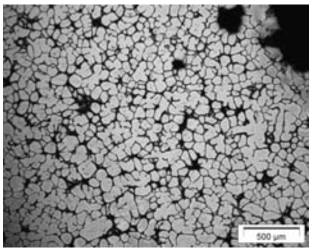
- melting of precursor billets in induction heated SiC crucible
- holding for 5 min. at 20°C above liquidus line

- pouring into steel vessel assuring laminar flow
- air cooling of vessel surface
- at solid/liquid content of 50/50 water quenching of slurries

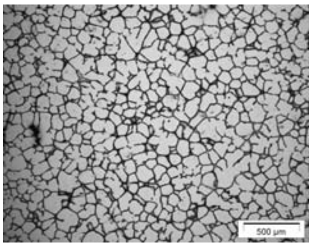
Fig. 13 provides the micrographs of the Al-Li-X systems, which were processed by the New Rheocasting route.



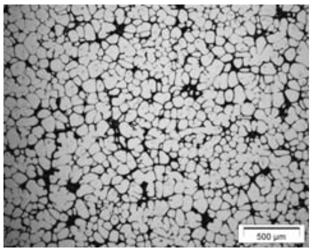
(AA2091) 667°C/633°C



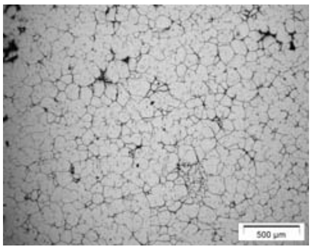
(AlLi2,5Cu4) 678°C/632°C



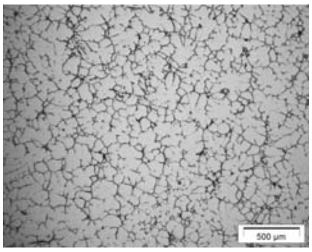
(AlLi1,5Cu4) 670°C/641°C



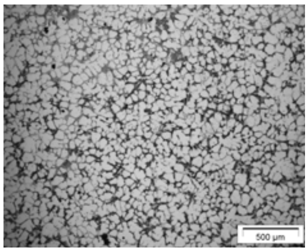
(AlLi4Cu4) 660°C/560°C



(AA8090) 670°C/640°C



(AlLi2,5Mg4) 670°C/618°C



(AlLi4Mg8) 620°C/520°C

Fig. 13 : NRC Al-Li-X microstructure after quenching from the semi-solid interval without grain refiner,1st temperature=casting temp., 2nd temp.=quenching temp.

Unfortunally it was not possible to suppress the formation of dendritic grains and micro-pores (**Fig. 13**). It is assumed that in the case of a suitable set of process parameters (super-heating temperature, undercooling rate, mould design etc.) the results can be improved. Nevertheless, the best results were obtained with the alloys AlLi4Mg8 and AlLi4Cu4. It is worth mentioning that none of the alloys were processed with the aid of grain refining elements as applied in the investigations on the conventional thixocasting process. It is likely to achieve globilitic grains with additions of AlTi5B1 grain refiner master alloy into the Al-Li-X melt and further investigations have to prove this assumption.

8 Inductive re-heating of Al-Li alloys

The reheating of the precursor billets took place in an inductive heating unit from Elotherm. The reheating unit has a horizontal single coil layout, allowing higher liquid fractions compared to the vertical setup. The billet is moved into the coil placed in a tray, **Fig. 14**. Due to the strong affinity to oxygen of the tested aluminium-lithium material a special billet tray had to be used.

The tray is made of magnetically soft stainless steel sheets to protect the re-heating unit. The billet holder is lined with a specifically designed insulation insert, which actually carries the semi-solid billet as shown in **Fig. 15**. Based on the experience of the reheating of highly reactive magnesium alloys, the composition of the insulating material has been adapted to Al-Li alloys. In order to prevent the billet from high temperature corrosion a cover with integrated argon gas supply was designed. With the aid of the thermodynamic calculations of the f_s-evolution combined with numerous re-heating experiments a first process window for Al-Li-Cu(Ti) as well as an Al-Li-Mg(Ti) alloy could be obtained.

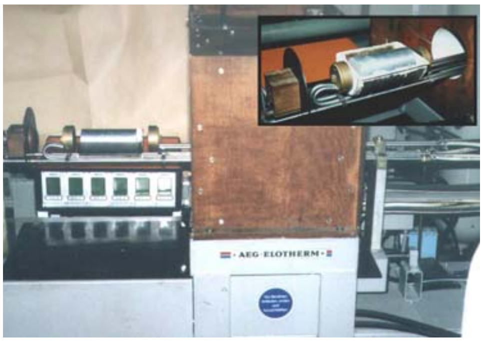


Fig. 14 : Inductive re-heating unit by Elotherm for single slabs of Al-Li alloys

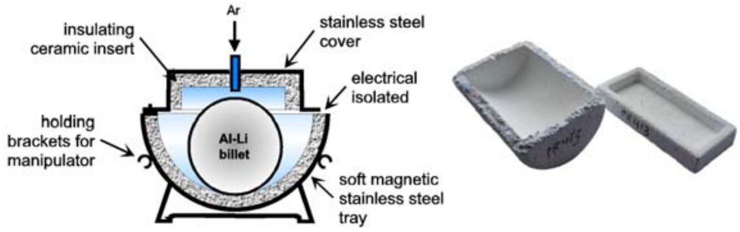


Fig. 15 : Schematic drawing of the billet tray and cover (left). Manufactured ceramic insulation insert in initial state (right).

In order to achieve the optimum softness of the semi-solid Al-Li alloys, the values of the energy input of the billet had to be adjusted (**Fig. 16**). The diagram shows the main control parameters of the unit as the frequency and current of the LC-oscillator, voltage of the convertor and the target as well as the calculated workpiece energy. The workpiece energy is calculated for a defined setup of the tuned circuit. The energy input into the billet is controlled through the voltage output of the transformer. **Fig. 17** shows the run of temperature against time for the two investigated alloys. The billets are 3” in diameter and 160mm in length. After 420 seconds the temperature field inside the material is completely homogenised and thus the billets are ready for casting. In order to prevent the billets from high temperature corrosion during the reheating cycle the billets were covered in tin-foil, pictured on the left side of **Fig. 17**. Due to the high energy input which is applied in the first heating stage the aluminium foil starts to glow slightly, **Fig. 17** (right). Although the foil melts partly the billet is effectively protected. The experiments have indicated that the magnesium containing alloys have not necessarily to be protected by a foil, if an adequate inert gas atmosphere is ensured. All reheated billets attained a very fine mushy structure and good softness at the investigated processing temperatures of 562°C (Al-Li-Mg) and 601°C (Al-Li-Cu), corresponding to a fraction solid of approximately 50%. At higher values of the fraction liquid the billets tended to react or burn due to leaking fluid phase. After the reheating cycle is finished the semi-solid billet is manually transported to the preheated shot chamber of the high pressure die casting machine.

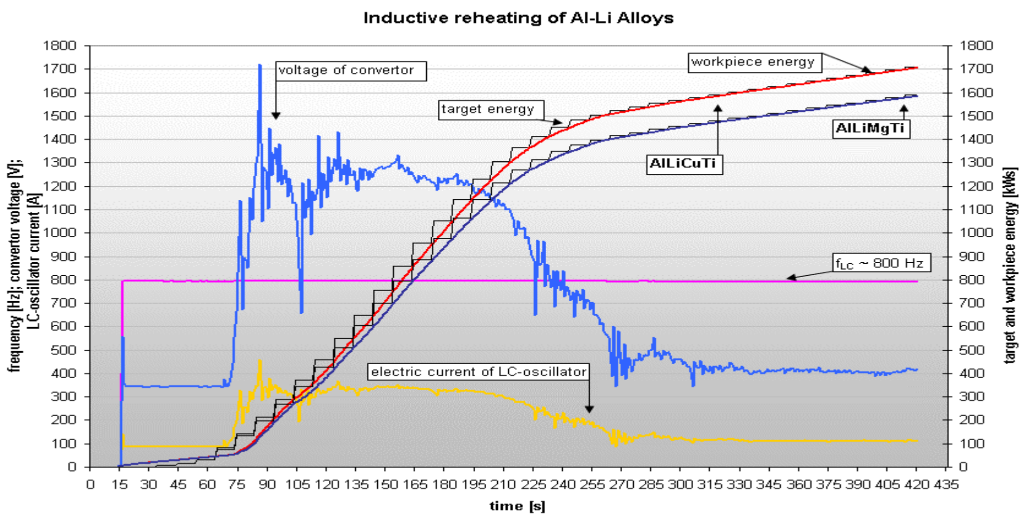


Fig. 16 : Data plot of the main control parameters as the preset target energy curve, the current and the frequency of the LC-oscillator and the inductor voltage as well as the numerically approximated workpiece energy.

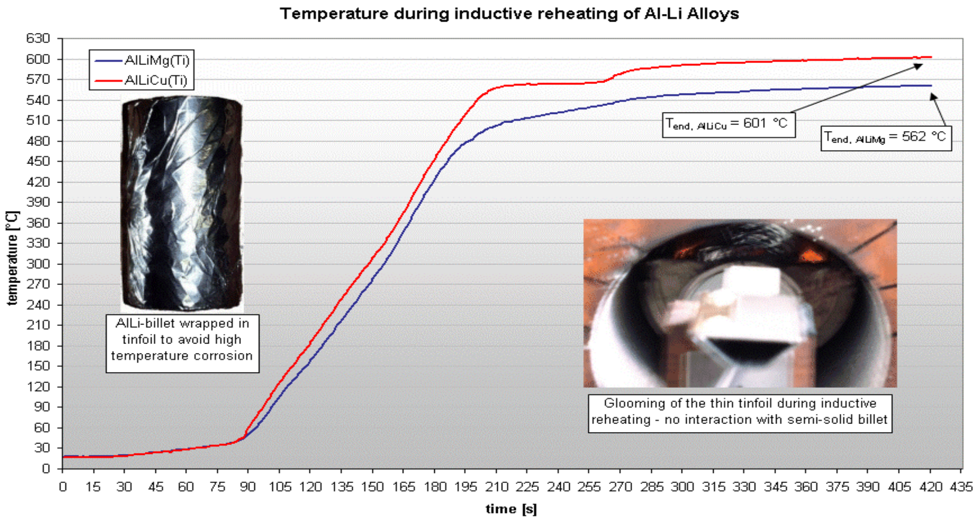


Fig. 17 : Time-temperature plot of a re-heating cycle of a 3" AlLiCu(Ti) and a AlLiMg(Ti) billet. In order to protect the billet from high temp. corrosion it has been wrapped in tinfoil (left upper). Glowing of the foil during inductive reheating cycle (right lower).

9 Thixocasting of Al-Li alloys

The investigations on the mold filling behaviour of semi-solid Aluminium-Lithium alloys have been performed on a modified, real time controlled cold chamber high pressure die casting machine type Bühler H 630SC. The machine has a locking force of 725tons and is able to realize piston velocities varying from 0.02 to 8m/s. In order to investigate the flow behavior of semi-solid materials different die tools have been designed.

Shaping experiments on the mold filling behaviour in dependence of the wall thickness have been carried out on a modular step-die. The step-die consists of the ingate including an oxide restraint system and seven interchangeable segments of specified thickness, which allow examinations on wall-thickness in the range of 25 to 0.5mm, representing the spectrum of industrial components. A schematic drawing of the step mold dimensions is given in **Fig. 18.**

For example at a constant piston velocity of 0.5m/s during mold filling, defined metal velocities in the range of 2.2 to 115m/s occur. In addition the interchangeability of the modular steps permits the investigation of different die materials and coatings. In order to reduce high temperature corrosion of the semi-solid Al-Li alloys a vacuum system can be adapted.

The dies are heated up by 3 oil temperation units to a maximum oil temperature of 350°C, leading to an average die temperature of 240°C. Any contact of semi-solid Al-Li material and tempering oil should be minimized to reduce the danger of high temperature corrosion of the cast metal and sudden blazes inside the die. Therefore the oil tempering units should work in suction mode, in order to reduce the oil pressure and thereby the leakage of oil.

The illustrated as cast demonstration part in **Fig.18** was produced using an Al-Li-Mg(Ti) billet at a piston velocity of 0.5m/s. The part could nearly be filled up to the bleeder and the characteristic of the fill-front indicates laminary flow behavior inside the mold. After solidification of the cast metal the component is ejected together with one part of the die casting tool. The so called restraint system can afterwards easily be removed from the part.

In order to avoid problems during the ejection sequence, attention has to be payed to the solidification time. Early ejection leads to abrupt blazes of the partly semi-solid biscuit, which suddenly gets in contact with the atmosphere and starts to react. **Fig. 19** shows a lightly burning biscuit after early ejection. On the left hand of **Fig. 19**, a Al-Li-Cu(Ti) part is depicted. In comparison to this, the magnesium alloyed pre-material achieves higher surface quality and accuracy as well as marginally better flow and mold filling properties. Both alloys show a very fine globular primary phase with small eutectic inclusions embedded, **Fig. 19** (below). The distribution of the solid phase is almost uniform along the complete step mold part.

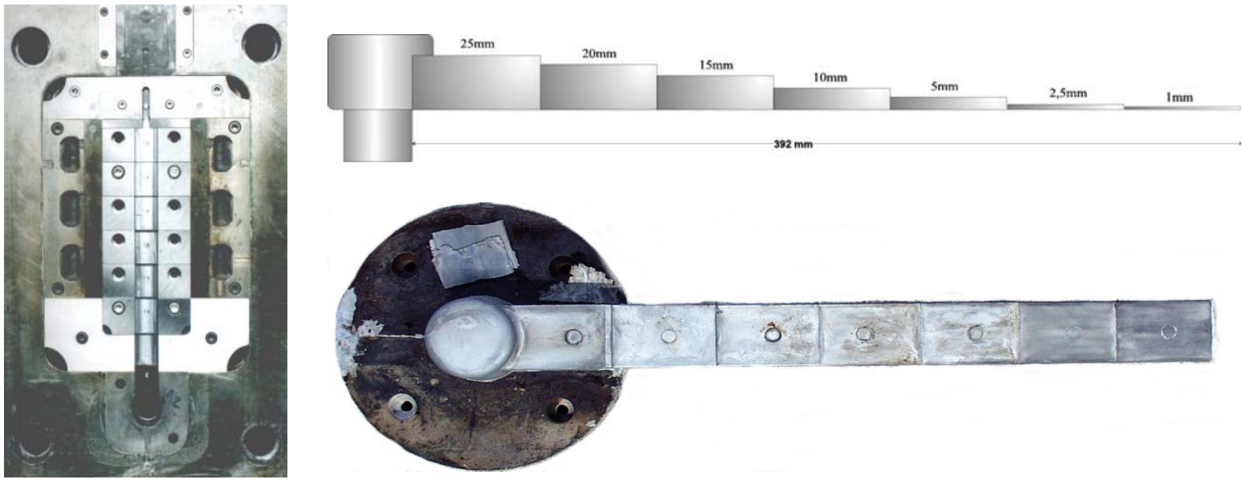


Fig. 18 : Modular step mold with interchangeable inserts of varying wall thickness from 0.5-25mm (left). On the upper right hand a schematic drawing of the step die used in the experiments is shown. Thixocast AlLi-alloy part at a fraction solid of about 50% including the oxide restrain inserts. (below).

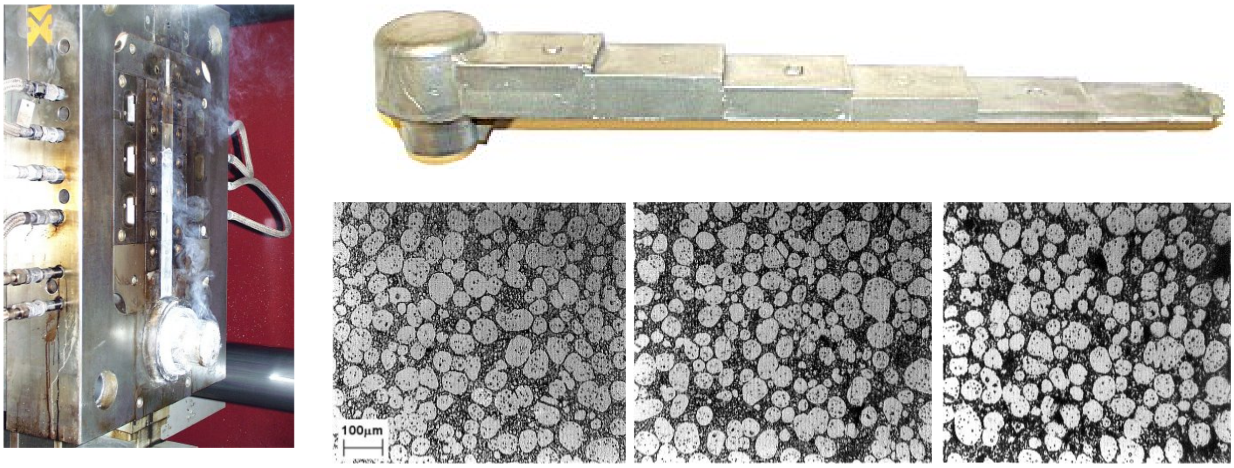


Fig. 19 : Due to early ejection of the part strong oxidation reactions of the hot an partly semi-solid biscuit can occur, respectively (left). The alloys exhibit good mold filling properties and surface quality (upper right). The sound flow behaviour is a result of the very fine microstructure (AlLi4Mg8Ti0,2). The distribution of the fraction solid is almost unaltered along the complete step mold part (l.r.: 2.5mm, 1.5mm, bleeder).

The investigations on thixocasting of highly reactive Lithium alloyed light metals using a cold chamber die casting machine show very promising results in terms of process safety and stability as well as component properties. Therefore extensive research on mold filling and solidification behavior will be carried out in the near future within the cooperative research action SFB 289 to evaluate a reliable process window for this innovative light metal concept.

10 Assessment

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, recycability and high material and processing costs.

In this work we report about the potential and future prospects of near-net shaping Al-Li alloys in the semi-solid state. 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. **Table**

5 provides some results of the evaluation of the "thixoformability" of the investigated Al-Li alloy systems.

Thermochemical calculations and DTA experiments did help to identify suitable alloy systems. With the aid of chemical grain refining it was possible to manufacture a suitable Al-Li precursor material with a fine and globular grain structure as well as sound flow behavior for proper subsequent semi-solid processing, in particular AlLi4Mg8Ti0,2 and AlLi4Cu4Ti0,2. The potential of New Rheo Casting (NRC) conducted with AL-Li alloys is rated lower than the Conventional Thixo Casting route (CTC).

Table 5: Investigated Al-Li alloys and assessment of "thixoformability"

Alloy	Cu	Li	Mg	T_{50}, °C	df_L/dT	D, μm	Formfactor FF	Rating*
A1(AA2090)	2.5	2.5	–	637	0.023	116	0,42	3
A2	4.0	2.5	–	629	0.015	137	0,4	2
A3	4.0	4.0	–	605	0.0083	82	0,67	1
A4	4.0	1.3	–	639	0.024	107	0,39	3
A5 (AA8090)	1.2	2.5	0.7	638	0.026	130	0,43	3
A6	–	2.5	4.0	613	0.012	83	0,38	2
A7	–	4.0	8.0	542	0.0044	52	0,4	1

* 1=good, 2=middle, 3=bad

Future developments will focus on further adjustment of the chemical composition and micro-alloying in order to evaluate and obtain good mechanical and corrosion properties with semi solid processed Al-Li components.

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