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Semi-Solid Processing of Tailored Aluminium-Lithium Alloys for Automotive Applications**

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This paper describes the development and evaluation of thixoformable Al-Li-Mg-based alloys performed at the collaborative research center SFB 289, RWTH Aachen. Scandium and zirconium were added to AlLi2.1Mg5.5 (A1420) with the aid of DoE (Design of Experiments), and precursor billets were manufactured by pressure induction melting (PIM). To evaluate the thixoformability of the synthesized alloys semi-solid processed connecting rods were manufactured by the rheo container process (RCP). Subsequent heat treatment raised the mechanical properties to maximum values of tensile strength, 430 MPa, yield strength of 220 MPa, and an elongation to fracture of 13 %. The RCP process was designed for the special requirements of highly reactive alloys. The paper presents the remarkable property and process benefits of the semi-solid processing of Al-Li alloys.

1. Introduction

The development of commercially-available aluminium-lithium-based alloys was initiated by adding lithium to aluminium-copper, aluminium-magnesium, and aluminium-copper-magnesium alloys. These alloys were chosen to superimpose the precipitation-hardening characteristics of intermetallic AlCu, AlCuMg and AlMg precipitates on those of lithium-containing precipitates [1]. In the process, the alloys A2020 (Al-Cu-Li-Cd), A1429 (Al-Mg-Li), A2090 (Al-Cu-Li) and A2091 and A8090 (Al-Cu-Mg-Li) evolved.[2–4] However, no specific casting alloys on an Al-Li basis are available which might offer a greater freedom of shape forming, and only a few research works on this topic are known.[6] The challenges of Al-Li alloy manufacturing and processing today are:

– Hot tearing susceptibility in the casting process
– High reactivity of lithium with refractory materials, moisture and atmospheric gas
– High scrap rate / high machining costs due to a high rejection rate
– Corrosion susceptibility
– Recycling issues
– Al-Li alloys cost three times more than conventional Al alloys

Processing Al-Li alloys in the semi-solid state offers a high potential to overcome some of these difficulties. Porosity, volume shrinkage and hot tearing susceptibility should be significantly improved due to the lower liquid phase content of

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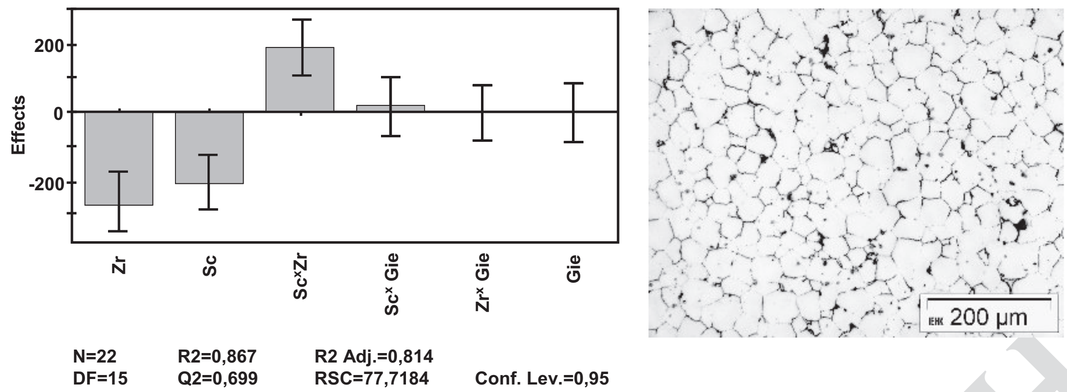


Fig. 1. Statistical effects of Sc and Zr addition (single addition and mixture) and the casting temperature (Gie) on the grain size of the alloy AlLi2.1Mg5.5ScZr (A8) (left); example of the microstructure of a billet (right).

40–60 % during the thixoforming process. Machining and overall costs are reduced because of it is possible to manufacture near-net-shape components. With the rheo container process developed at the Foundry Institute of Aachen University,[10,11] a suitable tool is available to handle the high reactivity of Al-Li alloys.

2. DoE-Supported Synthesis of Al-Li-Mg-Based Precursor Material

Up to 0.3 wt-% scandium and zirconium were added to the well-known alloy AlLi2.1Mg5.5 (A1420). The other influencing parameter which was varied was the casting temperature (750–850 °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. The high reactivity of lithium with atmospheric gases and refractory material and its high equilibrium vapour pressure makes it necessary to use specialized melting and casting techniques. A lithium-resistant SiC crucible was installed in a 3 bar argon overpressure induction melting furnace. The melt was poured under protective gas into a steel mould, forming billets of approximately 3 kg total mass.

The target of minor element addition was to minimize the average grain size within the billets in the as-cast condition. Figure 1 illustrates that the effects of Sc and Zr addition on the resulting grain size are statistically significant, while on the other hand the variation of casting temperature has no influence on the grain size. Using this synthesis route the grain size can be adjusted statistically securely and reproducibly via Sc and Zr addition. Figure 2 shows the contents of Sc and Zr needed to achieve a certain grain size in the alloy. The mathematical model predicts a grain size of 30 µm 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. This grain-refined precursor material was used for the subsequent semi-solid Rheo Container Process.

3. RCP Processing of Al-Li

The rheo container process (RCP) is a rheocasting process which takes into account the needs of highly reactive alloy systems such as magnesium or Al-Li alloys. One special characteristic of the process is its use of a non-returnable container. After pouring the liquid alloy into an aluminium container with a wall thickness of 1mm, the alloy cools to the target processing temperature in the container. Due to the "slurry on demand" procedure the utilisation of a reheating device is unnecessary.[12] The container is transferred together with the semi-solid billet to the shot chamber of a die-casting machine and pressed into the die (Fig. 3). The folded container re-

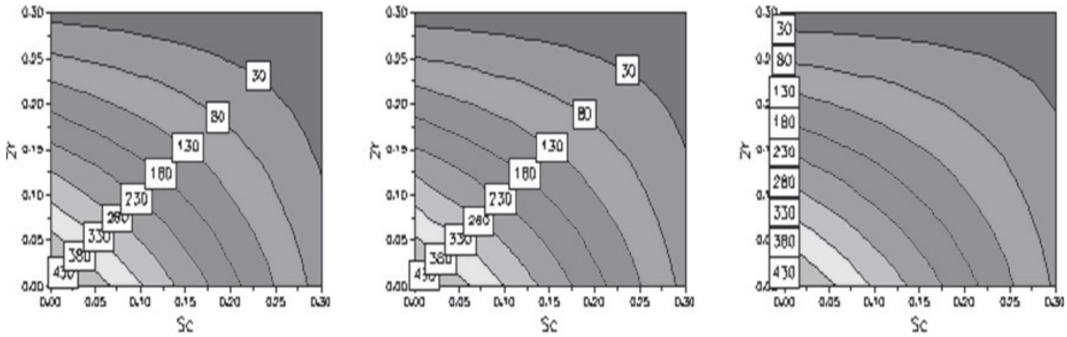


Fig. 2. Dependence of the average grain size in µm on Sc and Zr content for the alloy AlLi2.1Mg5.5ZrSc at 3 different casting temperatures (left: 750 °C; centre: 800 °C; right: 850 °C).

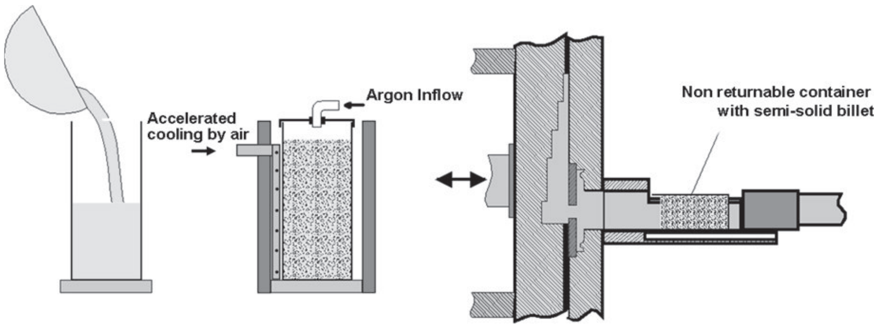


Fig. 3. Schematic illustration of the rheo container process (RCP).

mains completely in the biscuit.[13] Cooling to the semi-solid state was supported by air blowing.

The main advantage of the procedure is its prevention of the formation of an oxide layer, creating the best conditions for the processing of highly reactive alloys. Excepting the top side of the billet, no contact takes place between either the melt or the semi-solid-material and the atmosphere. Even the top side can be easily protected from the atmosphere by using a cover with argon inflow. The use of the non-returnable container avoids recycling problems, because it also consists of aluminium.[5] To implement the RCP process for Al-Li alloys, additional aspects had to be considered, especially in the area of melt handling. Due to the high reactivity of the alloy Al-Li2.1Mg5.5Zr0.15Sc0.15, the melting furnace was sealed up and flooded by argon. The processing of the semi-solid Al-Li alloy was executed on a real-time-controlled high-pressure die-casting machine by Buehler (H-630 SC).

4. Results

To investigate the suitability of the rheo container process (RCP) for the processing of highly reactive Al-Li-alloys, an automotive connecting rod was selected as a model product. The mechanical properties, the melting loss and the microstructure were analyzed for each shot. Out of the cast connecting rods, flat bar tension specimens were sectioned and tested. Figure 4 shows the sampling locations and the good homogeneity of the microstructure over the total length of the component.

4.1. Mechanical Properties

The mechanical properties were analyzed as-cast and after a standardised T6 heat treatment. Figure 5 shows the results of the tensile tests carried out. The error bars define the upper and lower results.

Via heat treatment the mechanical properties of A1420 (AlLi2.1Mg5.5+ Sc and Zr) were improved significantly. In this way the tensile strength was increased to over 400 MPa, the yield strength up to 250 MPa and the elongation to fracture to an average of 6.4 %, almost three times higher than in the semi-solid cast condition.

4.2. Improvement and Adjustment of the Heat Treatment Process

To investigate the improvement potentials of the heat treatment, sectioned samples of the connecting rod were solution-annealed (24 h 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 (Fig. 6). 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/10 h, 160 °C/25 h or 140 °C/> 35 h.

4.3. Strengthening Effects During Heat Treatment

While the melt solidifies it forms an alpha solid solution. As a result of the controlled cooling rate in the container, the primary alpha phase grows in a globular form. At a tempera-

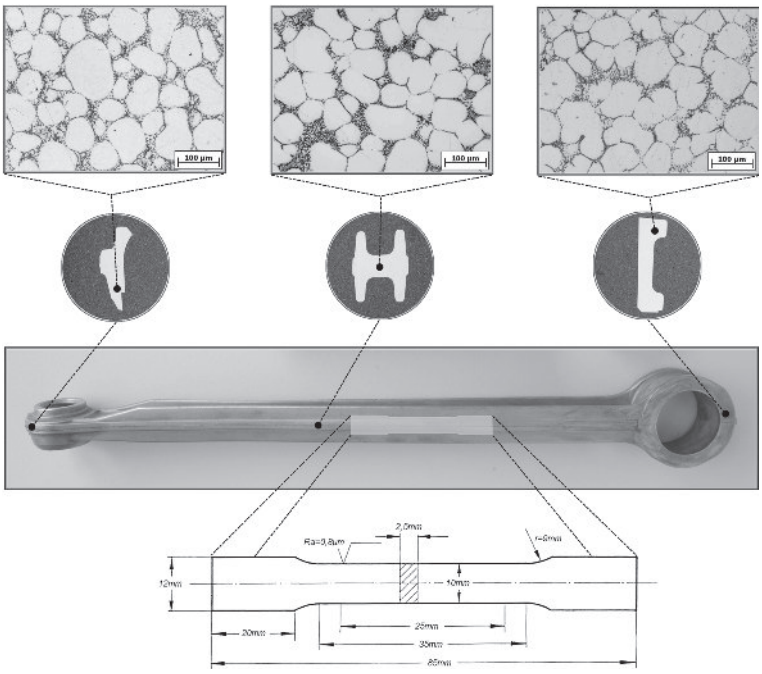


Fig. 4. Sampling of flat bar tension specimens and microstructure homogeneity of a semi-solid cast Al-Li automotive connecting rod.

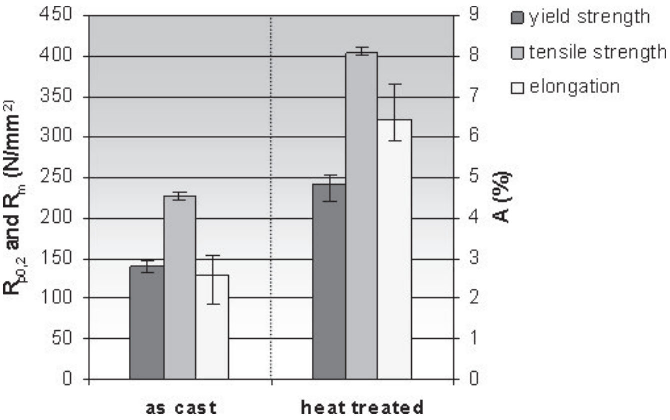
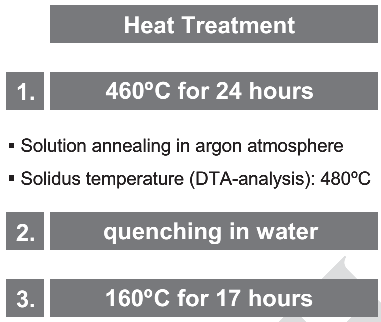


Fig. 5. Mechanical properties of A1420 + Sc and Zr, as-cast and T6 heat-treated.



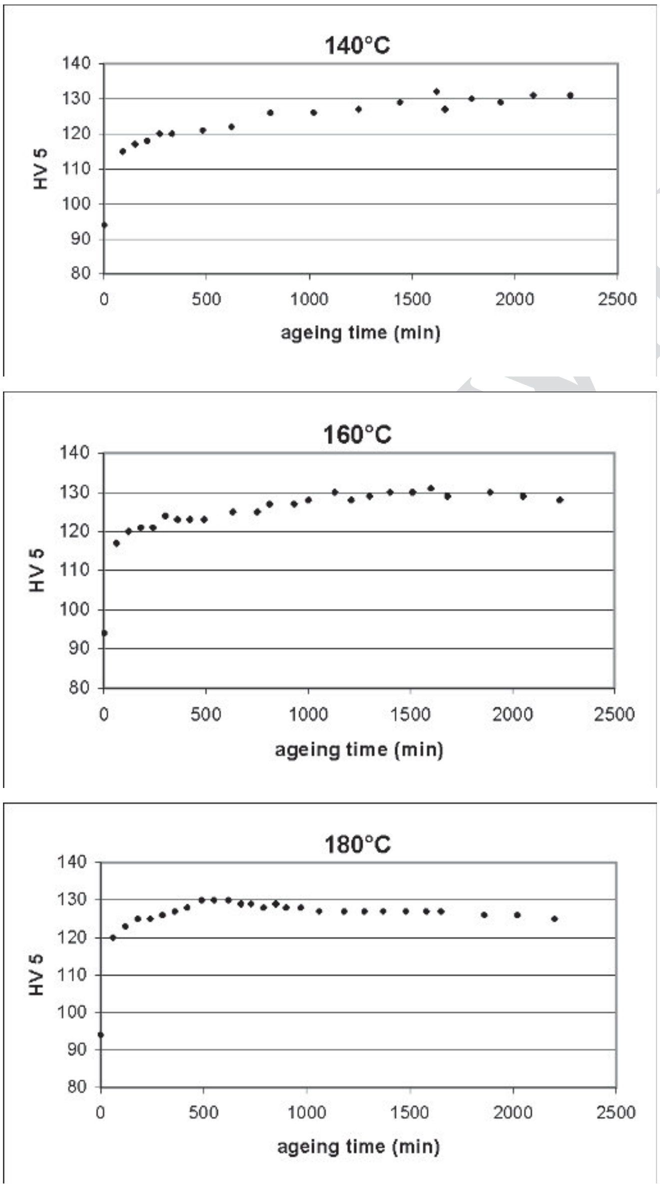


Fig. 6. Ageing of A1421 connecting rod samples at 140, 160 and 180 °C.

ture of about 600 °C, equal to a solid fraction of about 0.5 (calculated by Thermo-Calc and based on the Scheil model), the container was transferred to the high-pressure die-casting machine and pressed into the steel die. Rapid solidification of the remaining melt then took place in non-equilibrium by the formation of "unexpected" eutectic, including the phases Al_2LiMg, $Al_{12}Mg_{17}$ and Al_8Mg_5[7] (Fig. 7) .

During heat treatment for 24 hours at 460°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 (Fig. 7).

The added elements Sc and Zr formed $Al_3(Sc_xZr_{1-x})$ dispersoids, which inhibited undesired grain growth during the solution treatment.[8,9]

After water quenching from the solution temperature the components were aged for 17 hrs at 160 °C under argon atmosphere. According to literature, the primary strengthening phase Al_3Li was formed.[8] Due to the limitations of the EDX the existence of nanometer-sized Al_3Li could not be verified. With the aid of the ageing treatment a remarkable increase in strength and elongation was achieved.

4.4. Chemical Homogeneity

Because of the high reactivity of lithium and magnesium with atmospheric gases, moisture and refractory material, the oxidation loss of Li presents a big challenge in the melting of aluminium-lithium-magnesium alloys. Therefore a carbon crucible was used for remelting, due to its good stability against lithium. The rheo container process also possesses the advantage that the contact between melt and atmosphere is minimized by using an aluminium container. The melt is additionally protected from atmospheric gases by encapsulation and flooding with argon. The result is that the alterations which take place between start and cast compositions are acceptable (analysis by SPECTROMAXx). The results are shown in Table 1. Due to the limitations of the spectrometer, strontium could not be analysed.

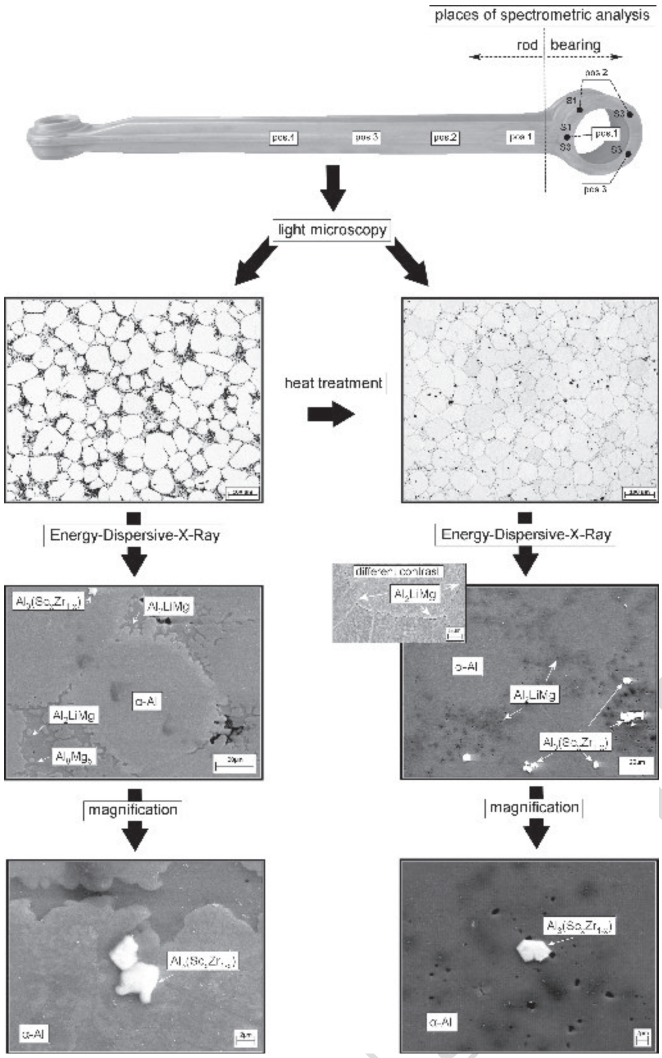


Fig. 7. Microstructure of Zr/Sc-microalloyed A1420. Left: as-cast; right: heat treated; measuring points with detected phases.

To evaluate the melting loss in the process the cast connecting rods must be compared with the precursor material billets. With an average concentration of 1.7 % lithium and 5.16 % magnesium, the measured results of the precursor billets differ from those of the targeted concentrations (2.1 % and 5.5 %, respectively). This is the result of the burnoff of Li or possibly the segregation of Li and Mg in the precursor manufacturing.

Between rod and bearing no significant differences could be identified. Therefore the manufactured connecting rods can be assumed to be homogeneous.

On an overall average the lithium loss during the rheo container process is 24 %, and that of magnesium only 7 %. However, this loss of alloying metal is primarily caused by remelting the billets, which indeed took place under argon inflow, but obviously insufficiently. This was especially noticeable as dross formation while remelting, whereas during cooling in the container almost no dross appeared. With a capsuled remelting process in a controlled atmosphere it is possible to significantly decrease the reactions of highly-reactive alloying additions.

4.5. Hot Tearing Susceptibility of Al-Li Alloys

The components feature areas which are difficult to cast, especially at the bearing points, where the semi-solid flow fronts meet. Figure 8 shows casting defects (microscopic and macroscopic) as well as fully acceptable areas.

In the rheo container process the hot tear susceptibility of Sr/Zr microalloyed A1420 remains a problem. In fact, while no tear-free connection rod was manufactured in this test series, macro cracks were only found at one of the bearing points. Because a non-preheated steel core was used in this problematic area the melt solidified too rapidly and could not rejoin. Interestingly, this difficulty was not seen at the opposite bearing point, where there was no cold steel core and a shorter flowing length. In future, with suitable process parameters and suitable tools, it should therefore be possible to manufacture tear-free components from complex castable wrought alloys such as A1420 using the rheo container process.

Table 1. Spectrometer analysis of two Sc/Zr-microalloyed A1420 samples. The Positions 1 to 4, are located from the ingate to the large bearing of the connecting rod (Fig. 7); The deviation (*) is calculated versus the precursor billets (1.7 % Li, 5.16 % Mg).

	rod [wt%]						bearing [wt%]				
AlLi-1	pos.1	pos.2	pos.3	pos.4	ø	deviation*	pos.1	pos.2		ø	deviation*
Li	1.24	1.30	1.30	1.29	1.28	0.42	1.26	1.26		1.26	0.44
Mg	4.88	5.08	4.85	5.08	4.97	0.19	4.67	4.94		4.80	0.36
Zr	0.106	0.112	0.125	0.103	0.112	0.038	0.103	0.131		0.117	0.033
AlLi-2	pos.1	pos.2	pos.3	pos.4	ø	deviation*	pos.1	pos.2	pos.3	ø	deviation*
Li	1.30	1.33	1.33	1.36	1.33	0.37	1.35	1.33	1.31	1.33	0.37
Mg	4.75	4.91	4.71	4.93	4.82	0.34	4.75	4.82	4.53	4.70	0.46
Zr	0.069	0.067	0.074	0.069	0.070	0.08	0.061	0.079	0.072	0.071	0.079

5. Assessment, Summary and Outlook

Processing Al-Li alloys in the semi-solid state offers a variety of benefits. Up to now Al-Li alloys have

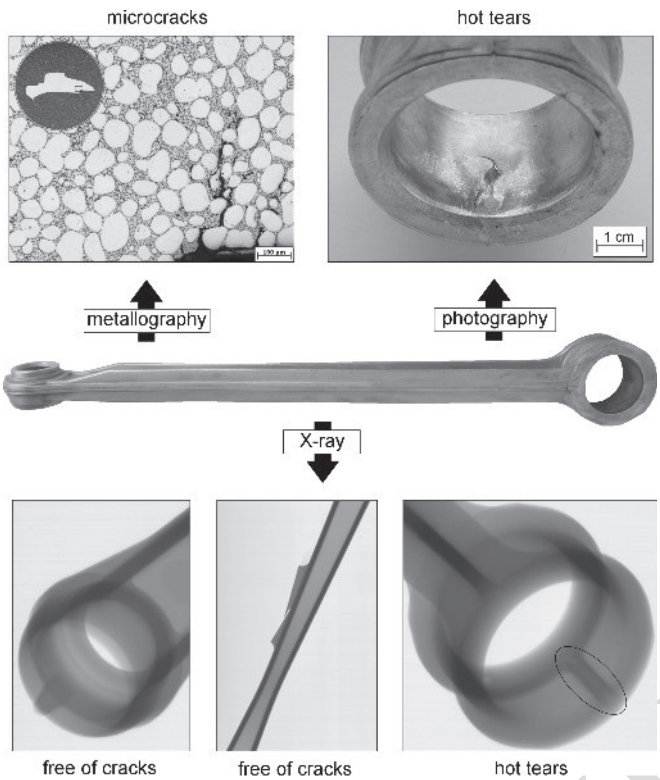


Fig. 8. Selected failures of the casting defects of the connecting rod in miscellaneous sizes: microcracks and hot tears.

Table 2. Comparison of mechanical properties of Al-Li-X alloys.

		Product		Rp0,2%	R_m	A
Alloy	Heat treatment	Shape (process)	direction	(MPa)	(MPa)	(%)
8090	T6	Cast structure (casting)	indepen-dent	281	347	3,7
8090	T8	Sheet 4 mm (rolling)	L LT L-45	404 416 377	475 487 460	6,0 7,0 9,1
1421 (+ Sc)	#	Sheet 2–5 mm (rolling)	L LT L-45	360 380 339	469 500 470	8 10 15
1420 + 0,15Sc0,15Zr [connecting rod – this work]	T6	Cast structure (semi-solid)	indepen-dent	255	410	7

 # Air quenched from solutionising temperature + 3-stage aged, L – in rolling direction, LT – 90° to rolling direction, L-45 – 45° to rolling direction

generally been wrought alloys processed by rolling, extrusion and forging. Specific Al-Li casting alloys which offer a high degree of freedom of shape are still unavailable for commercial use. Challenges which need to be addressed for Al-Li alloys are their high reactivity, hot tear susceptibility, the occurrence of brittle intermetallic phases, chemical corrosion, recyclability and high material and processing costs. Due to the reduced liquid phase content compared with conventional fully liquid casting it is possible to remove some of the problems which occur in conventional Al-Li alloy processing. With the aid of a suitable heat treatment concept this research work proved that semi-solid processed near-net-shaped Al-Li-Mg connecting rods can reach static mechanical properties in the range of those of rolled A1421 (AlLi2.1Mg5.5ScZr) (cf. Tab. 2**)**. Future developments will focus first on AlLiMg prototypes processed by SSM and on further improvement of heat treatment strategies.

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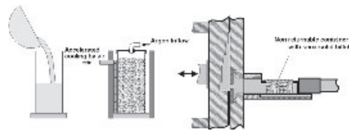

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