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New tailored high strength & ductile Al-alloys for laser powderbed fusion (LPB-F)

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Abstract

Laser material processing like laser-beam welding or powderbed fusion (LPB-F) of Al-alloys have demonstrated many options for light weight structures & sustainable by function driven designs. Scalmalloy®, an AlMgSc material concept developed by Airbus, commercialized by PAG APWorks, offers outstanding good material properties in LPB-F ($R_m \geq 500$ MPa) but suffers on LPB-F process stability due to complex interactions of laser energy (its physical conversion into melting heat) with its physical bulk material absorption & reflection propensities. Replacing Mg by Cr enables a new and promising Al-material concept (ScanCromAl®). First investigations at Airbus Central R&T showed that AlCrSc alloys can offer a very good strength-ductility property mix owing an unexpected solidification micro structure in comparison to AlMgSc.

Keywords: Scalmalloy®; Mg-evaporation; LPB-F; high strength; AlCrSc; ScanCromAl®

1. General remarks on direct material creation by additive manufacturing technologies

Since many decades near net shape manufacturing procedures have attracted design & manufacturing engineers because they promise competitive benefits in terms of costs, environmental (sustainability) aspects as well reduced time to market. The ascent of laser & electron beam assisted powderbed melting about 20 years ago promoted these manufacturing approaches significantly. In particular laser powderbed fusion (LPB-F) also called Selective Laser Melting (SLM) which defines a layer by layer material creation concept enabling complex 3-dimensional parts & structures has fertilized new material opportunities. Due to thin build layer thicknesses (generally less than 100 µm) in combination with a high intensity laser beam ($\geq 10^6$ W/cm² peak power) propagating with 500 – 2000 mm/sec through this metal powderbed, rapid solidification of the molten metal will occur. Consequently, the directly layer-wise generated product material volume comprising of thousands or even millions of single laser melting (welding) tracks with metal powder as filler. LPB-F-printed parts quality depends directly from the selected alloy composition and the LPB-F process parameters.

Thanks to rapid solidification during LPB-F material creation engineers can benefit from a much larger field of alloying possibilities compared to incumbent casting or welding processes. A material (alloy chemistry) adjusting for improved material strength including post LPB-F process heat treatments to offer strength in combination with convincing ductility becomes viable. In addition there is an increasing interest in tailoring metals for LPB-F using extended data bases and computational thermo-dynamical modelling (Integrated computational material engineering (ICME)) to predict material properties depending on chemistries & process routines. Though, relative successful from a pure material perspective, it haven´t yet proven to fully comply with the complex multi parameter physical challenge of the laser energy interaction and target alloy (substrate). Especially, for Al-alloys there is still much room for improvements to develop alloys promising a stable & reliable LPB-F process.

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2. High performance Al alloys by LPB-F processing

2.1. Al-Sc alloy possibilities in tailored LPB-F based material creation

Since about 50 years Scandium (Sc) is a part of industrial Al-material research [1]. Its major Al-alloying propensities are well understood. Sc shows very high precipitation hardening capability in Al (up to 40 – 50 MPa strength improvement for 0.1wt% Sc by nano-sized Al_3Sc fully coherent particles decomposed from a super-saturated solid solution [2].

Rapid solidification procedures like powder atomization enables the use of high Sc contents beyond equilibrium limits of 0.38 wt% to achieve products strength beyond 600 MPa [4]. The very low mismatch of the $L1_2$ - Al_3Sc phase with respect to the Al lattice favors good controllable heat treatments at about 250 – 350°C which secure nano-sized (< 10 nm) fully coherent Al_3Sc precipitation particles [3]. It also affects grain refinement & recrystallization inhibition capabilities quite comparable to Zr (like other transition metal elements fostering a heterogeneous nucleation mechanism) [5,6].

However, due to its scarcity and related high costs a comprehensive deployment of Sc as alloying element was only realized in Russia for military & space applications [6]. Fortunately, this has been changed over the last 10 years significantly. Today, Sc_2O_3 ("Scandia") as a precursor compound for AlSc master alloy manufacturing is readily available because it can be leached out from waste material streams like "red mud" (bauxite refinement) or "waste acid" (TiO_2 – "white pigment" manufacturing). As both material sources are distributed worldwide comprising millions of tons, future supply chains of Sc or AlSc master alloys can be seen as safe and sustainable.

Scalmalloy®, an AlScMg material concept developed & refined by Airbus at 2000 - 2010 was the very first alloy that deliberately combined the Al-Sc metal physics with unique rapid solidification opportunities offered by LPB-F. Depending on Mg (which enables solid solution strengthening) and Sc content (which promotes precipitation hardening after post LPB-F process annealing in combination with Hall-Petch fine grain hardening), ultimate tensile strength values beyond 650 MPa at material densities down to 2.62 g/cm³ are possible still displaying a reliable ductility of > 10% fracture elongation and 20% of fracture area reduction. The reasons for this impressing material performance are a very special bi-modal extremely fine grained micro structure and a very high density spherical nano-sized Al_3Sc particle evolution [7].

However, beside principal material properties other additive manufacturing process challenges like the layer-wise material creation are of major concern as well. It turns out that the (high) Mg content in Scalmalloy® "stimulates" undesired process dynamics during LPB-F. The predominant evaporation of Mg due to its low boiling temperature and the complex laser energy transfer mechanism are causing an unstable, permanently fluctuating melt puddle with high amount of spatter responsible for inconsistent material densities.

Hence, future tailoring of Al-alloys for LPB-F will have to fulfil material strength properties needs as well serve much better LPB-F processing capabilities. Molten alloy viscosity and surface tension are known to manipulate the melt puddle dynamics. Preventing Mg would minimize "smoke" (= MgO reaction) evolution. It is known from laser welding trials that the addition of transitions metal elements like Fe, Ti, Zr, Ni, Co etc. can influence laser welding (melting) process stability positively (decreasing key-hole porosity). Therefore, future LPB-F centered Al-alloy optimization should address such material opportunities.

2.2. AlScCr-alloys for LPB-F manufacturing

Chromium is an interesting alloying element for Al-materials. However, its low max. solubility of about 0.7 wt% promotes the creation of Al_xCr_y phases when executing classical material manufacturing procedures like sheet or plate rolling or extrusion. Consequently, currently Cr is only used as a minor alloying element (≤ 0.2 wt%) in selected Al-alloy compositions to foster defined AlCr dispersoid evolution to be used for micro structure control during intermediate or solution annealing steps (recovery, primary & secondary recrystallization or grain growth inhibition). There are other important factors that makes Cr interesting for Al-alloys tailoring w.r.t. to LPB-F:

- Cr additions in Al aren´t critical to Sc as no melt-solidification reaction has to be expected (which would deplete a new AlCrSc alloy from Sc jeopardizing Al_3Sc hardening capabilities) [2]
- Cr is building like Al & Sc a stable protective oxide (Cr_2O_3)
- Cr manipulates laser beam melt puddle dynamics due to its viscosity increasing propensity [8]

Based on these observations it was decided to run a 1st research study on LPB-F of an AlCrSc alloy (composition see table 1). Like for Scalmalloy® a comparable material concept becomes viable when using different amounts of Cr combined with adjusted Sc contents. Certainly, there are further opportunities for adding other elements to master process and increase strength behavior. Anyhow, we call the AlCrSc material concept: ScanCromAl®.

Table 1. Composition of investigated AlCrSc alloy with comparable Sc/Zr content like "standard" Scalmalloy® but no Mg

Element	Al	Cr	Sc	Zr	Fe	Si	Ti	Mg
wt %	Rem.	2.6	0.72	0.25	0.06	0.01	0.01	0.01

The ScanCromAl® alloy was LPB-F processed using almost spherical AlCrSc powders manufactured by Toyal, Hino, Japan. It was nitrogen atomized featuring a powder size distribution of about 10 – 75 µm. Figure 1 is showing ScanCromAl® while processed in Ar gas conditions in a 400 Watt SLM Solutions 125HL LPB-F building device showing a clean and spatter-poor process in contrast to Scalmalloy® where a strong "smoke" evolution together with dark deposits on freshly solidified material are typical. Enhanced LPB-F process stability of ScanCromAl® was also proven by metallographic analysis of LPB-F material solidity preparing selected cross sections (s. figure 2). Investigation on chemical composition of directly generated material disclosed no significant discrepancies in the alloying element contents verifying that alloying element loss (like known Mg-depletion in Scalmalloy®) isn´t any more an issue in ScanCromAl®.

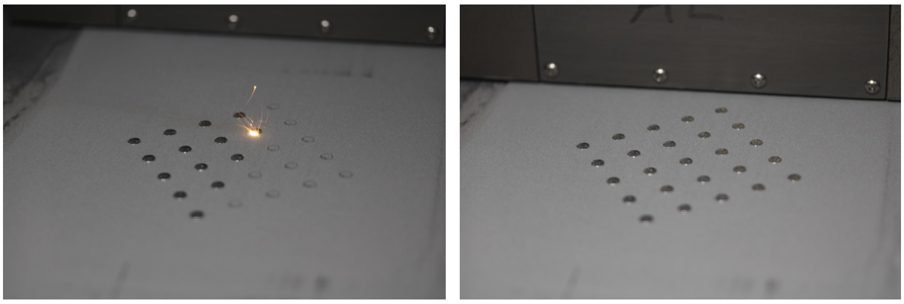

Fig. 1. AlCrSc alloy during LPB-F processing (no "smoke" evolution & reduced spatter) & after processing ("stainless steel look")

After selection of the most appropriate process parameter tensile test bodies (in accordance to DIN 50125 – B4 x 20) were manufactured, fully machined and tested following ISO 6892-1, to screen ultimate tensile strength (UTS), yield strength (YS), fracture elongation (A) and reduction of fracture area (Z).

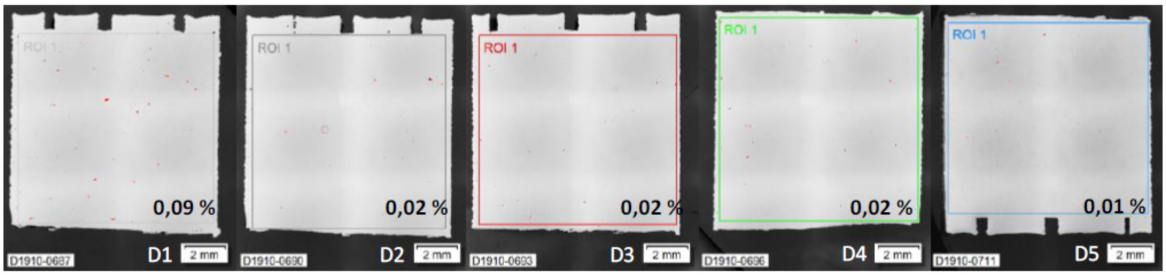

Fig. 2. LPB-F "density cubes" of LPB-F processed AlCrSc with different LPB-F process parameter

Precipitation hardening capabilities of the bulk material was pre-tested & controlled by a larger test matrix where one & 2-step heat treatments in the range from 250 – 400°C / 2 – 16 h were executed using an ambient air furnace. Via Brinell hardness measurements optimum temperatures as well heat treatments durations are fixed. Almost doubling of the Brinell hardness was possible (70 – 75 HB as built conditions ⇔ 145 -150 HB in peak aged conditions) proving the desired precipitation hardening reaction for the tested AlCrSc alloy.

2.3. Strength assessment on the LPB-F generated AlCrSc material

All tensile test samples were tested in vertically built direction ("Z"- direction). Figure 3 depicts the static properties of the AlCrSc alloy comparing "as built" in contrast to annealed states with 3 different heat treatment schemes (350°C/2h / 275°C/2h + 350°C/2h / 375°C/8h).

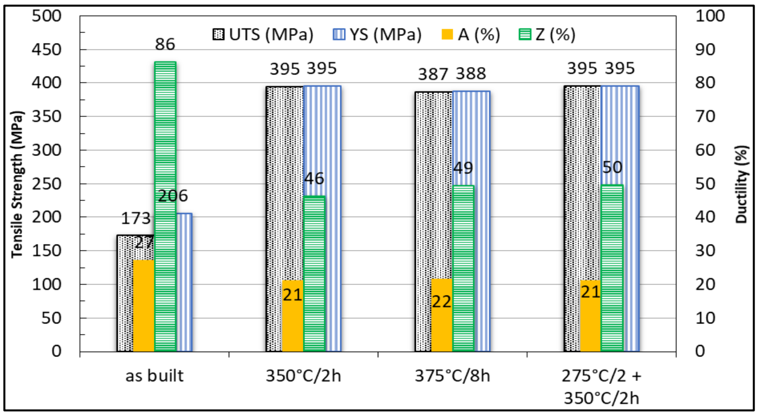

Fig. 3. Static strength values of AlCrSc alloy in the "as built state" & annealed 350°C/2 – 375°C/8h – 275°C/2h + 350°C/2h

The strength investigations revealed some surprising features. We see in the "as built" configuration a relative low strength (UTS) together with an enormous material plasticity (nearly 30% fracture elongation with more as 80% reduction in fracture area). Precipitation hardening annealing enables a significant strength (UTS) increase close to 400 MPa. This fits quite well to the hardness measurement. The stress-strain plots displayed very low strain hardening tendency but convinced with pretty good all over plasticity. The 2-step 275 / 350°C heat treatment seems to establish a slightly better ductility in the material although offering equivalent strength values. In addition the AlCrSc alloy proved to be very stable with respect to annealing temperatures showing only a minor over-aging when heat treated at 375°C/8h.

2.4. AlCrSc micro structure peculiarities

Micro structure analysis was done with metallographic means (Baker´s etch) followed by SEM investigations (including EBSD) to clarify & correlate the exceptional strength/ductility properties of LPB-F generated AlCrSc. In Scalmalloy® the LPB-F material comprises a bi-modal structure where extreme fine globular sized grains (0.5 – 4 µm) are layer-wise altering with small columnar shaped grain clusters (length ≤ 25 – 30 µm) which are visible in each solidified material build layer when inspected perpendicular to the built direction. An explanation for this extraordinary micro structure incorporates a heterogeneous nucleation mechanism caused by non-coherent Al_3Sc particle and possibly some Al_2O_3-MgO oxide particles. Surprisingly, in AlCrSc, although metallurgically very similar to AlMgSc, the bi-modal very fine grain structure is replaced by large columnar grains, which are oriented in (cooling) heat flux direct direction. They can grow over many build layers and reach lengths beyond 200 µm (fig. 4). The horizontally dark or bright shadowed boundary layers in the pictures below are Al_xCr_y particles.

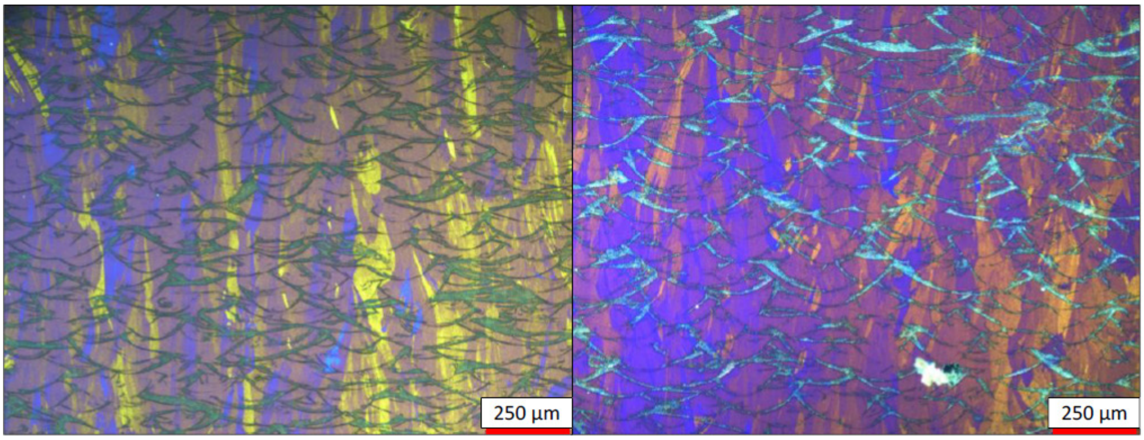

Fig. 4. Metallographic inspection perpendicular to build direction of AlCrSc in polarized light – Baker´s etch depicting large columnar grains

The reason(s) why a Cr addition in contrast to Mg is altering this well-known Sc-related grain refinement mechanism is still unclear. Here, further investigations are necessary.

3. Conclusions & outlook towards future work

The substitution of Mg by Cr in AlSc alloys enables a more robust LPB-F processing and still allows full usage of the Sc-related precipitation hardening capabilities. Surprisingly and not at all expected, we see a totally different micro structure in AlCrSc alloys if compared to AlSc or AlMgSc alloys. Instead of the known very fine grained bi-modular structure now large columnar grains are prevalent. Anyhow, all over strength-ductility performance is very convincing. This encourage us to drive further investigations on modified AlCrSc alloys to reach UTS values beyond 500 MPa. In addition, deeper metal-physical analysis to understand & disclose the surprising solidification behavior is necessary.

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