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Process and Mechanical Properties: Applicability of a Scandium modified Al-alloy for Laser Additive Manufacturing

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Abstract

The applicability of an aluminium alloy containing scandium for laser additive manufacturing (LAM) is considered. Modified aluminium alloys with a scandium content beyond the eutectic point offer great potential to become a high prioritized aerospace material. Depending on other alloying elements like magnesium or zirconium, strongly required weight reduction, corrosion resistance and improved strength properties of metallic light weight alloys can be achieved. The development, production and testing of parts built up by a laser powder bed process will be presented with regard to the qualification of the new material concept “ScalmalloyRP®” for laser additive manufacturing.

*Keywords:*Laser Additive Manufacturing (LAM); scandium; Al alloy; ScalmalloyRP; mechanical properties; microstructure

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1. Introduction

Although high performance materials like carbon fibre reinforced plastics gain more and more importance, aluminium alloys will furthermore play an important role in aircraft industry in the future. Existing Al-alloys were improved within the last few decades and static strength properties have reached a level over 600MPa (e.g. 7xxx or 2xxx Al-alloys). But not only improved strength properties are required for structural efficiency of high performance aerospace applications, high plasticity as well as good corrosion and fatigue resistance has to be guaranteed. Over the last years scandium and zirconium as alloying elements have become a major interest for researchers all over the world [1-9]. The improvements of properties that can be achieved by adding these elements to an Al-alloy are remarkable. Depending on the composition a significant increase of strength behaviour by precipitation hardening after annealing as well as grain refinement can be achieved [2,7]. Higher strengths (e.g. at 7xxx Al-alloys) are normally associated with an increase of corrosion susceptibility and decrease of ductility. Scandium is the key element of alloy investigations at EADS Innovation Works since 2002 regarding the combination of high strength properties with a reduction of density.

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These alloy investigations were based on 5xxx AlMg-alloys, which offer high solid solution hardening addiction as well as an improved corrosion resistance. The main idea of the material concept Scalmalloy® is now to combine these positive effects to get an optimized all-in-one high strength Al-alloy. Literature has shown that high cooling rates are necessary to freeze a hypereutectic Al-Scandium composition in solid solution [1-2].

Increasing requests of new metallic material concepts are closely connected with the application of new and improved manufacturing methods. Rapid manufacturing techniques became great attention in the aerospace community because they enable a rapid development of complex and topology optimized parts with few process steps. Lightweight structures can be manufactured with a high degree of geometric freedom and almost without manufacturing limits. New design possibilities like thin walled structures or complex lattice interior structures can be considered by the application of additive manufacturing concepts of metal parts. A virtual model is sliced into several layers which are built up successively. Meanwhile there are several of additive techniques available. The laser based powder bed technique, used for the following investigation, offers powder layers of a certain thickness in which the target geometry is melted by a laser. The central question then becomes: Does the laser melting process offer rapid solidification with cooling rates that are sufficient to keep all alloyed scandium in a hyper eutectic Al-scandium composition? In this case, how might the use of LAM affect the properties of ScalmalloyRP material?

2. Experimental procedures

There are variants of suitable alloy systems depending on the percentage of scandium and magnesium applicable at the moment. ScalmalloyRP0,66-4,5 with a moderate scandium content of 0,66wt.% and a relative high content of 4,5wt.% magnesium was chosen for the first series of tests. Fabrication of the metal powder was done by gas atomization. Aluminium scandium master alloy (2 wt % Sc) was molten and magnesium, manganese, and zirconium were added. The composition of the alloy was determined chemically and is given in Table 1.

This ScalmalloyRP powder variant was combined with a laser based additive manufacturing process that realizes a layer wise fabrication of a 3D structure from CAD-data. That is done by melting or welding lattice structures directly in the metal powder layer of a predefined thickness. For the following investigation, the EOS M 270 machine was used. Influencing process parameters are 1st laser related (laser power, spot size etc), 2nd powder related (particle shape, size, distribution, layer thickness etc.) and 3rd scan related (scan speed, scan strategy, scan spacing) [10]. Scanning was divided in two different modes. The contour mode was used for the outline of the cross section, and the fill mode was used for the rest of the cross section. This was done because of accuracy and surface finishing reasons [10]. The Laser power of the EOS machine is limited to 200W, therefore it was set to 195W and a layer thickness of 20µm was chosen. To determine scan related, applicable parameters for an equally and non-porous consolidation of the welding paths, 20 test cubes were manufactured within one build sequence by variation of hatch distance and scan speed. The microstructure of each cube was evaluated by means of optical microscopy at various magnifications. After this initial study tensile test specimen were built up in three different orientations (different angles of 0°; 45°; 90°) and afterwards mechanically milled in accordance to DIN 50125.

The most suitable ageing response was expected at 325° for 4 hours [3, 8-9]. To assess if the desired hardening effect of Al3Sc precipitates occurs, Vickers hardness tests were done on one test cube in “as built up” condition and in “after artificial ageing” condition. Afterwards all tensile test specimens were aged at 325°C for 4 hours.

After testing the tensile test specimen in accordance to DIN EN ISO 6892 the fracture appearance was characterized macroscopically and also microscopically with a scanning electron microscope.

Table 1 chemical composition of ScalmalloyRP0,66-4,5 (wt.%)

Alloy	Sc	Mg	Zr	Si	Fe	Cu	Mn	Cr	Zn	Ti	Ni	Pb	Sn
ScalmalloyRP0,66-4,5	0,66	4,5	0,37	0,17	0,068	<0,001	0,51	0,002	0,036	0,006	<0,001	<0,001	0,009

3. Results

3.1. Ageing response

Vickers micro hardness tests were performed to determine whether artificial ageing of the LAM ScalmalloyRP0,66-4,5 material at 325°C for 4 hours showed the desired effect. In Figure 1 two hardness curves (for “as built up”- and “after artificial ageing” condition) are shown. The average hardness (HV0,3) of the “as built up” cube is approximately 105. For the “after artificially ageing” cube, a value of 177 was achieved. The significant increase in hardness indicates a distinct hardening effect.

3.2. Microstructure

The results of the parameter study regarding density are shown in Figure 2. This matrix consists of micro sections of the test cubes for different scan speeds and hatch distances. A broadened hatch distance (in direction of arrow) leads to a noticeable loss of density as well as an increasing scan speed (in direction of arrow). For several process parameters micro pores occur in an acceptable range for the investigated application. The used combination (encircled in Figure 2) was chosen for the final build up of tensile test specimen time due to time restraints and an acceptable density value.

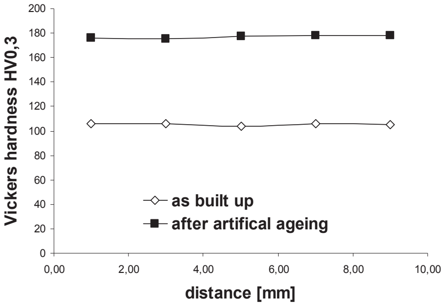

Figure 1. Vickers hardness curves of test cubes in as “built up” and “after artifical” ageing condition [325°C/ 4h]

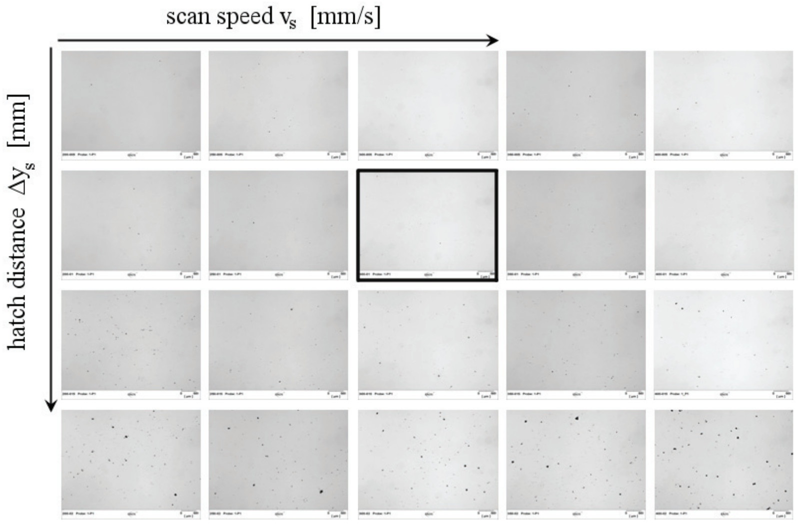

Figure 2. Matrix of parameter study with increasing hatch distance and scan speed; chosen parameter is encircled

3.2.1. Static mechanical properties

The average results of each orientation are shown in Figure 3(a). Each build-up orientation (0°; 45°, 90°) obtained yield strengths over 500MPa and tensile strengths over 520MPa. A correlation of the strengths with the build-up orientation was observed, although the variation of the strength behaviour was less than 5%. The test specimens tested parallel to the layer build up orientation, have the highest tensile strength with over 530MPa. In addition to the high strength properties, the ductility of the additive manufactured ScalmalloyRP material was remarkable. The mean elongation was 14% and the reduction of area was 20%.

3.2.2. Fractography

A precise fractography study of the fracture surface was performed after testing the additive manufactured and aged specimen. The facture appearance can be seen in Figure 3(b) - Figure 4(a),(b). It shows fast fracture at 45 °, a visible reduction of area, and the existence of micro pores. The reduction of area is one characteristic that indicates ductility. Furthermore, the fine dimple structures shown in fig Figure 4 (a) proves the occurrence of ductile fracture. In addition to ductility features, several types of inclusions are observed at the base of a few grains. Some fractographs also show small areas without full coalescence (Figure 4 (b)).

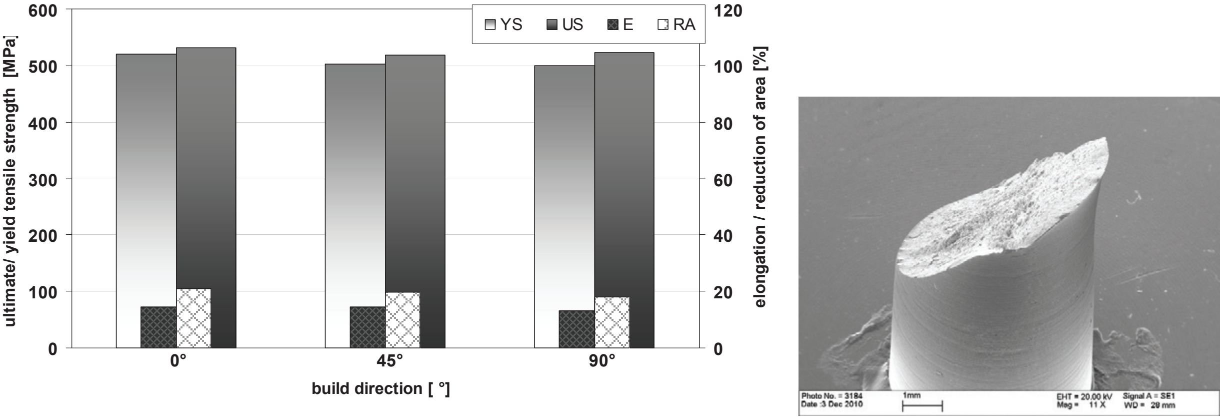

Figure 3. (a) Mechanical properties: ultimate strength, yield strength, reduction of are, elongation; (b) appearance of fracture: reduction of area

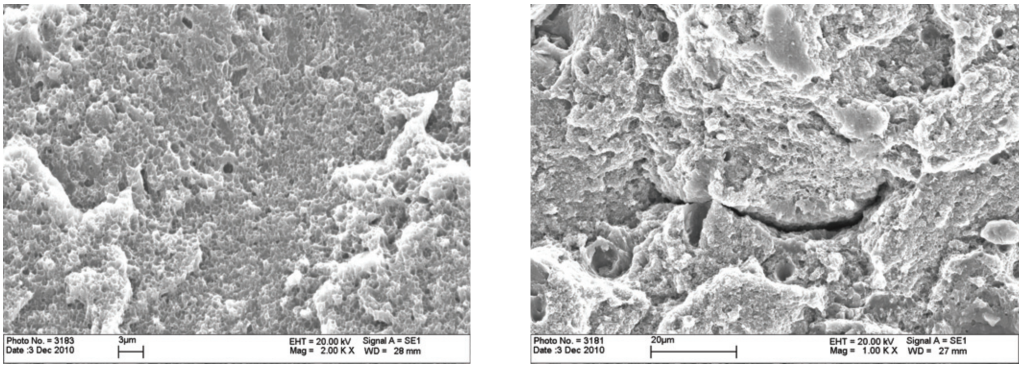

Figure 4. (a) appearance of fracture: dimple structure; (b) feature in microstructure without full coalescence

4. Discussion

The primary goal of ScalmalloyRP material for the use of additive manufacturing is to obtain a microstructure with maximum density while simultaneously forming a supersaturated solid solution. As described in literature [1-2], high cooling rates are required to constrain a supersaturated solid solution and to get high precipitation hardening effects after ageing. The addition of Scandium has enhanced the strength properties by forming a considerable amount of Al_3Sc after ageing at 325°C over 4 hours. A detailed investigation of the exact amount of Al_3Sc and/or $Al(Zr_xSc_y)$ precipitates will be done in further research. The precipitation hardening effect was most likely increased by the addition of Zirconium which precipitates on the Sc rich core, forming a shell. Magnesium is another element which contributed to the high strength results by solid solution hardening. It is established that Scandium leads to grain refinement in Al-Mg alloys and this has a major effect on the ductility. High elongation and reduction of area values for an Al-alloy are without doubt a proof of plasticity. The grain refinement was observed on several fractographs which showed areas of very fine grains of 1 µm. The existence of micro voids and process pores did not influence the static mechanical properties. Small micro cracks and areas without full coalescence arose during the laser melting process. Poorly bonded powder grains, layer or inclusions at the base of grains arise for example due to powder contamination or because of less convenient process parameter. Another test series will be done to indentify next to the grain size, the grain distribution of the powder regarding density and inclusions in grains.

The high strength properties indicate that sufficiently high cooling rates occurred during the laser additive manufacturing and that a supersaturated solid solution was realised. An unexpected high process stability level was achieved with a scatter of results less than 1% for each build-up orientation. The stress-strain-curves of the specimens were nearly identical for each orientation. The mean measured tensile strength of horizontally (0°) built up test specimens exceeded the measurement of vertical and 45° build ups by only 1,5% and 3% respectively. Nearly the same applies to the yield strength. The variation in each orientation in elongation and reduction of area was insignificant.

The suitability of the ScalmalloyRP for aerospace applications in combination with laser additive manufacturing is proofed. In Table 2 a comparison of alternatives to ScalmalloyRP and laser additive manufacturing is given. Another variant to produce complex high strength parts for aerospace application is, for example, milling of a 7050 plate. The ultimate and yield strength are equivalent to ScalmalloyRP material but only on the expense of ductility. On the other hand casting of AC42200 can provide higher ductility but it can not assure high strength mechanical values. Manufacturing restrictions regarding geometric freedom in contrast to laser additive manufacturing are for both, milling and casting, limited. One alternative, in combination with LAM, could be AlSi10Mg. The achievable strength properties are comparable to AlSi10Mg cast material but still circa 180 MPa lower than ScalmalloyRP strength values. The advantages of the combination of LAM and ScalmalloyRP are numerous and will be investigated in more detail in further research.

Table 2 Comparison of alternatives to ScalmalloyRP0,66-4,5 combined with LAM (mean values)

alloy [temper] + process	ultimate strength [MPa]	yield strength [MPa]	elongation [%]	geometric freedom [low - moderate - high]
7050 [T7651] + milling [L]	524	455	7	moderate
AC42200 [T6] + casting	320	240	6	moderate
AlSi10Mg + LAM	340	275	8	high
Scalmalloy RP0,66-4,5[325°C/4h] + LAM	530	520	14	high

5. Conclusion

- The applicability of a laser additive manufacturing process with ScalmalloyRP0,66-4,5 powder is proofed. A hyper eutectic Al-Scandium composition was achieved.
- The increase of hardness between non aged and aged test specimen is due to Al3Sc precipitates.
- Static mechanical properties exceeded the expected level. The addition of scandium led to high strength but ductile behavior. A grain refinement was achieved that caused high plasticity compared to other high strength Al-alloys (e.g. 7050)
- At this stage, there is no comparable alternative Al-alloy, regarding static mechanical properties, and manufacturing process, regarding geometric freedom.

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