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Tailoring Al-7Si-0.3Mg cast alloy properties to represent HPDC tensile and fatigue behaviour in component prototypes

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To produce prototypes with mechanical properties expectable from EN AC 46000 HPDC components, prototyping related processes such as sand and plaster gravity casting as well as proper alloying and post solidification processes need to be understood and adjusted. Therefore, the influence of process, composition and heat treatment on tensile and fatigue behaviour has been investigated for an EN AC 42100 alloy. Sand cast test samples comprised the base alloy in as-cast condition and T5 treated as well as a 2 wt. % Cu addition in as-cast condition. Plaster cast test samples consisted of the base alloy in as-cast condition and T6 treated as well as a 1.7 wt. % Cu addition in as-cast condition. Tensile and fully reversed bending fatigue tests (R=-1) have been performed and the results have been compared to EN AC 46000 HPDC values. Samples in heat treated conditions and with Cu addition exhibited superior tensile properties than the base alloy in as-cast state for both casting processes. Yield strength and elongation values for the sand cast T5 treated and with Cu addition samples were similar to the HPDC ones. In terms of fatigue behaviour, T6 treated and with Cu addition samples exhibited strength improvements for plaster cast samples, while no changes were observed for sand cast samples. Only sand cast samples exhibited similar fatigue behaviour to the HPDC samples. The sand cast T5 treated samples were found to produce the most similar overall mechanical behaviour to EN AC 46000 HPDC.

KEYWORDS: ALUMINIUM ALLOYS – PROTOTYPING – TENSILE PROPERTIES– FATIGUE PROPERTIES – SAND CAST – PLASTER CAST

INTRODUCTION

When large series of cast aluminium products is needed, the most common manufacturing procedure is high pressure die casting (HPDC). The dies and tooling costs for this process and the need for actual working conditions tests call for prototypes cast with other methods, typically sand or plaster processes. The difference between the mechanical properties of these prototypes and those expectable from HPDC components produces uncertainty in the test results. In order to produce representative prototypes with these processes, a further understanding of the relationship between process, composition and post-processing is needed. By controlling these, the mechanical properties of the prototypes can be adjusted.

Process variables include, among others, molten metal treatment, filling behaviour, local solidification conditions and defect content. Different mould materials, filling process and local solidification conditions provide different microstructures and defect content. Smoother and controlled fillings produce lower defects levels. Secondary dendrite arm spacing (SDAS) is commonly used as an indicator of microstructure fineness and cooling rate in Al-Si castings. Generally, higher cooling rates result in finer eutectic areas and intermetallics and higher degrees of solid solution within the aluminium matrix; All this results in higher tensile properties [1].

In terms of composition, the properties of Al-Si alloys can be further on controlled with additions of Mg and Cu, modification with Sr or Na and grain refinement with Ti or B. Mg up to a 0.7 wt. % has a strengthening effect through the precipitation of Mg_2Si and the transformation of the deleterious β-Al_5FeSi platelets into a Chinese script phase with a composition close to $Al_8Mg_3FeSi_6$. Above this value, it produces no further strengthening or matrix softening occurs [2, 3]. Seifeddine et al.[4] observed an increase in the tensile properties with additions up to 5 wt.% Cu to Al-7Si-Mg alloy in directional solidified specimens with no

significant increase in porosity; Shabestari et al. [5] observed an increase in tensile properties up to 1.5 wt.% Cu addition after which, properties dropped due to the increase of porosity associated to the Cu addition. This increase in porosity could be due to two factors: decrease of hydrogen solubility with the addition of Cu and the increase in the solidification range due to the ternary eutectic reaction at 525ºC [5]. Chemical modification of eutectic Si through Na or Sr additions transforms the Si plate-like particles in a more fibrous form enhancing the ductility with respect to the unmodified state [6]. Additions of Ti or B are used to promote nucleation of grains to improve the distribution of phases and porosity.

Post solidification treatments for Al-Si casting alloys are aimed at increasing component strength. Common heat treatments for sand and plaster processes are T5 and T6. T5 treatment aims to precipitate phases from solid solution present in matrix after casting. The effectiveness of the treatment is strongly dependent on the amount of solid solution in as-cast condition. Mould shake off after solidification is strongly recommended although not always feasible. T6 heat treatment consists of a solution heat treatment to dissolve and homogenize phases and spheroidize Si particles; a quench to retain as much solid solution as possible and aging to precipitate hardening phases [1].

Evaluation of the Cu addition effect on tensile properties has previously been done on laboratory prepared specimens. Fatigue tests are generally performed on highly polished specimens and the influence of casting skins is not evaluated. According to Kauffman [7], casting skins may produce residual stresses enhancing the performance of the tests.

This work aims to provide representative knowledge to select process, alloy and post processing variables for producing prototypes representative of EN AC 46000 HPDC components.

EXPERIMENTAL PROCEDURE

Materials and sample preparation

A commercial primary EN AC 42100 aluminium alloy, being considered a high performing cast alloy with low Cu, Zn and Fe contents, was used for both sand and plaster samples. For sand cast samples, degassing was performed with degassing tablets. Si modification with Na and grain refinement with TiBAl was done through master alloys. Cu chips were used for the samples with Cu addition. Castings were performed following the bending fatigue flat specimen geometry (**Fig. 1a**) with a parting line in the middle. After cooling, samples were blasted with 0.5 mm diameter stainless steel balls on all surfaces. T5 heat treatment was then performed to the corresponding samples for 5 hours at 180ºC.

Plaster cast samples were modified using Sr, followed by degassing with N for four and a half minutes. Melt was poured in moulds with the bending fatigue flat specimen geometry (**Fig. 1a**). Cu chips were used for the samples with Cu addition. T6 treatment consisted of solutioning at 530ºC for 6 hours in a Nabertherm L40/11 furnace and quenching in hot water followed by aging at room temperature for 24 hours plus 5 hours at 180ºC in a Nabertherm TR-120 furnace with air circulation.

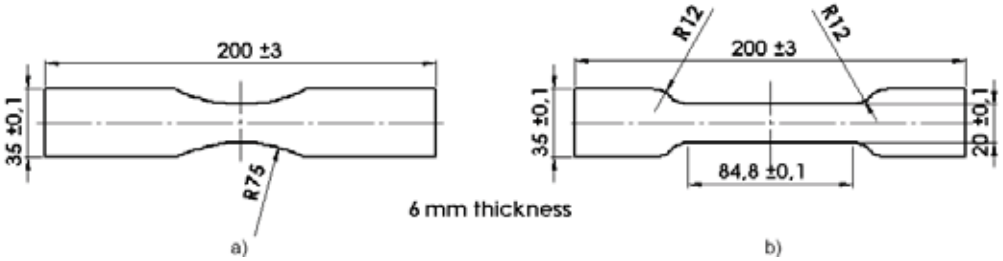

Fig. 1 – a) Bending fatigue geometry, b) tensile test geometry

Tensile and fatigue testing

Tensile samples (**Fig. 1b**) were machined from the fatigue test geometry. Tests were performed in a 100 kN axial capacity Zwick/Roell Z100 machine with a 20mm gauge length clip-on extensometer. Clamping pressure was of 100 mBar. A preload of 200 N was applied to straighten the samples. The test was position controlled with an elongation rate of 0.006 mm/s. A total of 5 samples for each condition was tested.

Fatigue testing was conducted in two cyclic multiple sample bending rigs. Tests were performed at a stress ratio of R=-1 (fully reversed loading) and 12 Hz frequency. Samples that did not fail after 3 x 10^6 cycles were considered run outs. A 3rd grade semi-logarithmic S-N curve was fitted to the results by the maximum likelihood method. 12 samples were used for each condition.

RESULTS AND DISCUSSIONS

Compositions for the different conditions is given in **Tab. 1**. It is important to note that the sand cast Cu addition condition has Si, Fe and Zn values over the intervals set for the EN AC 42100 alloy standard. Qualitative microstructural investigation revealed a coarser microstructure for the plaster cast samples with larger secondary dendrite arm spacing, implying a slower cooling rate, and a mix of fibrous and plate like eutectic Si areas. The sand cast samples displayed a full modification with a fibrous eutectic Si appearance. The porosity seemed to be the same for all conditions. Larger Fe-rich particles were found in the sand cast Cu addition samples compared to the other sand cast samples.

Tab. 1 – Chemical composition of tested materials (wt. %)

Chemical compositions											
Condition	**Si**	**Mg**	**Cu**	**Fe**	**Mn**	**Cr**	**Ni**	**Zn**	**Ti**	**Pb**	**Na**
Sand EN AC 42100	7.2	0.45	<0.01	0.12	<0.01	<0.01	<0.01	<0.01	0.14	<0.01	0.0038
Sand EN AC 42100 + Cu	8.3	0.42	2	0.31	0.08	<0.01	0.01	0.28	0.16	0.03	0.0046
Plaster EN AC 42100	7.1	0.25	<0.01	0.05	<0.01	<0.01	<0.01	<0.01	0.11	<0.01	<0.0001
Plaster EN AC 42100 + Cu	7	0.36	1.7	0.13	<0.01	<0.01	<0.01	<0.01	0.12	<0.01	<0.0001

Fig. 2 shows the tensile and fatigue curves. Representative values from the tests along standard and reference values for EN AC 46000 HPDC are presented in **Tab. 2**. In terms of tensile behaviour, with respect to the base alloy in as-cast condition, heat treatment and Cu addition produced an increase in Yield strength (YS) with a decrease in elongation to fracture regardless of the process. An increase of 11% and 92% in Ultimate tensile strength (UTS) was observed for the T5 and T6 treated samples respectively. The YS improvement for these same samples was of 32% and 213%. The corresponding decrease in elongation was of 43% and 74%. For the Cu addition, while no increase of UTS was observed for the sand cast samples, the plaster cast samples exhibited a 10% increase. In terms of YS, improvements of 23% and 48% were measured for the sand and plaster cast samples respectively, while the decrease in elongation was of 65% and 63%.

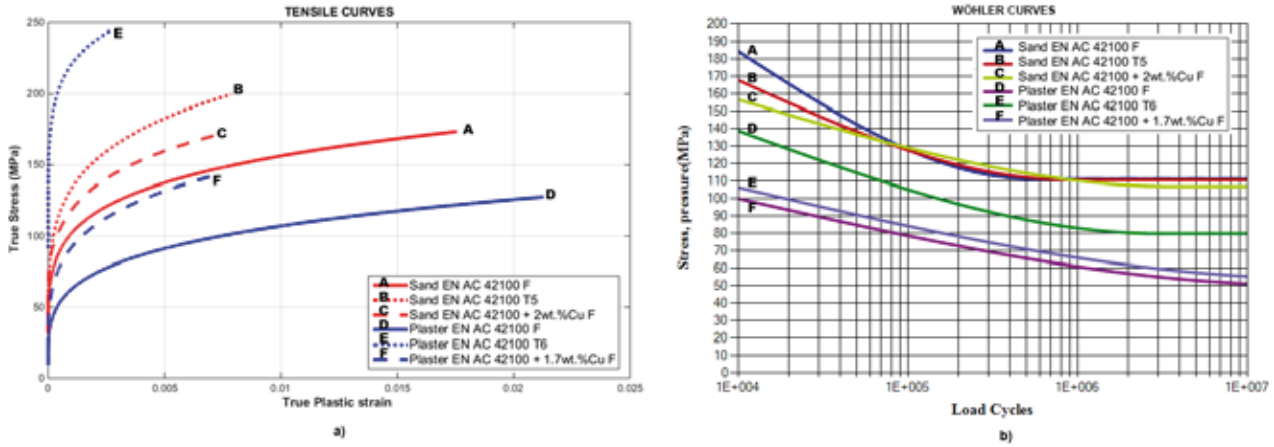

Fig. 2 – a) Tensile curves and b) Wöhler curves for the conditions tested.

Only the T6 treated samples reached UTS values comparable to the EN AC 46000 HPDC standard. The sand cast T5 treated and addition of Cu samples, and the plaster cast T6 samples showed YS values comparable or superior to the 140 MPa standard. In terms of elongation to fracture, the base alloys in as-cast state in both processes and the T5 treated samples produced values above the 1% in the standard.

With same elongation to fracture, higher UTS and YS values were achieved with the sand casting process for the base alloy in as-cast condition. This can be explained through the finer microstructure observed for the sand cast samples and is in accordance with the literature [1]. The increase in UTS and YS that the T5 treated samples exhibited is due to the higher cooling rate in the sand mould which produces enough solid solution after casting for the treatment to be effective. The high YS achieved with the T6 treatment suggests that underaging could result in lower values for YS [1] which would be more representative of the EN AC 46000 HPDC standard. It would also limit the decrease in elongation.

Tab. 2 – Tensile and fatigue properties of conditions tested and EN AC 46000 references

Tensile and fatigue properties						
Condition		**UTS(MPa)**	**YS(MPa)**	**E(GPa)**	**Elong. (%)**	**Stress at 1mcycles (MPa)**
Sand EN AC 42100	As-cast	169 ±3	117 ±2	69 ±7	2,0 ±0,1	111
	T5	188 ±9	155 ±7	71 ±6	1,1 ±0,4	111±9
	+2% Cu As-cast	169 ±5	144 ±5	74 ±5	0,7 ±0,1	110±15
Plaster EN AC 42100	As-cast	125 ±2	75 ±2	71 ±8	2,1 ±0,2	61±5
	T6	240 ±1	235 ±2	71 ±7	0,5 ±0,1	83±5
	+1.7% Cu As-cast	137 ±4	111 ±5	67 ±8	0,8 ±0,1	66±6
EN AC 46000	HPDC	225 ±18	167 ±2	72 ±2	1,1 ±0,3	109±11
	SS-EN 1706:2010	240	140		<1	

Regarding the fatigue characteristics, what may be observed in ***Fig. 2 b)*** is that performance was not affected by heat treatment or addition of Cu for the sand casting process. Since surface roughness can be considered the same, the similar fatigue performance could be due to the eutectic Si, qualitatively the same in terms of size, fraction and morphology, playing the major role in crack propagation. Notice that the stress values at 1mcycles for this process approached the Ys for the base alloy in as-cast condition. The case is different for plaster cast samples where the T6 treatment improved the fatigue performance displacing the Wöhler curve to higher stress values for this condition. The influence of the Cu addition for this process is not statistically representative. Qualitatively, the plaster cast samples presented a finer surface finish. Even so, the sand cast samples outperformed the plaster cast ones. Only the sand cast samples achieved values similar to the reference values from tests with the same sample geometry and parameters for EN AC 46000 HPDC.

It has been observed that in the testing conditions of this study, the main fracture initiation and propagation mechanism for the sand cast samples is not related to the composition or heat treatment but to the casting process. Surface roughness is widely regarded as a fatigue fracture initiation factor [7]; considering the results and difference in roughness of the samples observed in this study, it may be that the surface roughness played a secondary role in crack initiation, suggesting that internal near surface characteristics (pores, precipitates, inclusions, secondary phases) played a major role.

CONCLUSIONS

Regarding the effect of process, composition and heat treatment, it can be concluded that:

- For EN AC 42100 alloy, the sand casting process provides superior tensile and fatigue properties compared to the plaster casting process.
- T5 heat treatment or the addition of 2 wt. % of Cu to the sand cast EN AC 42100 alloy did not change the fatigue life.
- The addition of 1.7 wt. % Cu to the plaster cast EN AC 42100 alloy produced an improvement of UTS and Ys, a decrease in elongation and no change in the fatigue life.

From the point of view of producing representative behaviour, the T5 treated EN AC 42100 alloy cast in sand moulds produces similar tensile and fatigue properties to HPDC EN AC 46000 alloy and can be used for component prototyping.

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