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MECHANICAL AND THERMAL PROPERTIES OF RHEOCAST TELECOM COMPONENT USING LOW SILICON ALUMINIUM ALLOY IN AS-CAST AND HEAT-TREATED CONDITIONS

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Abstract

The growing demand for increasingly more cost and energy effective electronics components is a challenge for the manufacturing industry. To achieve higher thermal conductivity in telecom components, an aluminum alloy with a composition of Al-2Si-0.8Cu-0.8Fe-0.3Mn was created for rheocasting. Yield strength and thermal conductivity of the material were investigated in the as cast, T5 and T6 heat-treated conditions. The results showed that in the as-cast condition thermal conductivity of 168 W/mK and yield strength of 67 MPa was achieved at room temperature. A T5 treatment at 200°C and 250°C increased thermal conductivity to 174 W/mK and 182 W/mK, respectively, while only a slight increase in yield strength was observed. Moreover, a T6 treatment resulted in similar thermal conductivity as the T5 treatment at 250°C with no significant improvement in yield strength. Therefore, the T5 treatment at 250°C was suggested as an optimum condition for the current alloy composition.

Introduction

The castability, as well as mechanical and physical characteristics of cast aluminum alloys are influenced by both alloying and process conditions. In the high pressure die casting process (HPDC) of aluminum alloys, the main alloying elements are silicon (Si), magnesium (Mg), copper (Cu), iron (Fe) and manganese (Mn). Increasing the Si content in the hypoeutectic Al-Si alloy leads to better fluidity, castability and increased UTS but a decrease in elongation [1]. Mg and Cu are commonly added to improve mechanical properties. Adding Fe decreases the die soldering tendency but results in formation of Fe-rich intermetallic such as α-, β- and π-Fe phases in components. These phases are brittle and significantly decrease ductility of cast [2]. However, alloying element such as Manganese (Mn) principally modifies the Al-Fe-Si phase and improves both ductility and shrinkage characteristics of cast aluminum alloys [3]. The morphology and distribution of Si-particles from plate-like shape to a more fibrous shape through addition of modifiers such as strontium(Sr) or sodium(Na), increase ductility and ultimate tensile strength (UTS). Similar effects can also be achieved by an increased solidification rate and heat treatment [4].

The thermal conductivity of a material in steady state is a key property for applications where heat needs to be transferred away from a heat source generating a steady heat for instance an electronic device. Thermal conductivity of metals mainly depends on the mean free path of free electrons in a material [5]. The mean free path is influenced by alloying elements as the act as lattice defects or lattice imperfections. Lattice defects, in general, scatter electrons and decrease their mean free path. The magnitude of the interaction between the electrons and the lattice defects depends on the difference in electronic configuration between the solute and the solvent and on how much the impurities disturb the lattice. This also be determined by the alloying element and if the atoms are present in solid solution, as Guinier Preston (GP) zones, as larger precipitates or as particles [6]. An increase in resistivity has been observed for different aluminum alloys were clusters and GP zones are formed [7]. When the precipitates grow larger they will have smaller influence on resistivity [8]. Moreover, contribution of alloying elements outside of solid solution to the resistivity is typically one order of magnitude smaller compared to the contribution from elements in solid solution [9].

For many industrial applications, extruded aluminium alloys having low alloy content are used as excellent mechanical and physical characteristics can be achieved, especially in heat treated condition. However the extrusion process is limited to geometries having two-dimensional cross sections and only by combining with machining operations and/or assembly and joining operations more complex geometries can be achieved at a significantly higher manufacturing cost. On the other hand, the use of aluminum alloys with low amounts of alloying elements are not very common in casting due to poor castability resulting in casting defects and inhomogeneous microstructure in the final product. Overcoming to this obstacle may be possible using new innovative casting processes such as Semi Solid Metal (SSM) casting that has showed capability to cast novel materials, otherwise impossible to use in traditional casting methods.

As a rule of thumb in SSM casting, alloys with moderate solidification temperature intervals are the best choice for slurry preparation to obtain robust process conditions [10]. However, compared to HPDC, SSM-HPDC of near-to-pure aluminum alloys to fabricate a component have been shown to improve characteristics cast components. This was achieved due to the presence of pre-solidified particles (α_1-Al particle) in the slurry, which decreased the tendency for turbulent flow due to increased viscosity compared to traditional HPDC casting. In addition to this, a reduced shrinkage porosity was also achieved due to the presence pre-solidified material, reducing the overall shrinkage in the metal entering the die cavity. These characteristics of SSM-HPDC hold the promise to cast fully heat treatable components including also T6 treatments, today very un-common for cast components using traditional HPDC casting [11].

In this paper, thermal conductivity of a developed low-Si containing aluminum alloy, Alloy X, in a rheocast component was investigated. The objective of study was a better understanding about the effects of Si and Mn on primarily thermal conductivity in a rheocast material. Benchmarking to 6082 was made as this material has a well-known low Si aluminum alloy mostly used in in. The target of application was SSM cast components for telecom components.

Experimental Procedure

Rheocasting

A low Si containing alloy, Alloy X, with composition shown in Table I was prepared for rheocasting in this study. The slurry was made using the RheoMetal™ technique [12]. The shot weight was approximately 3 kg and the melt holding temperature was 665°C, corresponding to a 15°C superheat. A standard cast iron ladle was used. The Enthalpy Exchange Material (EEM) was 6-7% of the shot weight and stirring was made at 900 rpm. The final slurry temperature was 645±1°C. The casting experiments were made on industrial scale, using a 400 tons HPDC machine with the same cycle time as for the standard HPDC casting process of the component. The first and second stage injection speed and die temperature were kept fixed and regarded as optimized.

Table I. Composition [wt.%] and liquidus temperature of Alloy X used for experimental work, Al is balance

Alloy	Si	Fe	Cu	Mn	Zn	Mg	T_M [°C]
X	1.86	0.78	0.78	0.29	0.12	-	651
6082	0.89	0.19	<0.1	0.4	<0.2	0.59	-

The schematic of the rheocast component is shown in Figure 1. In the runner, the maximum thickness was around 20 mm and in the gate thickness decreased to 4.5mm. Maximum thickness of the component was 2mm. For this study, 20 components were manufactured and four tensile bars from near-to-gate region and near-to-vent locations of the component were produced. Sample 1 and 5 were tested in as-cast condition and samples 2 and 4 were tested in different heat-treated conditions. A total of 80 samples were tested in as cast and heat treated conditions. All thermal conductivity measurement were made from samples taken from the runner due to the required thickness of samples for the Laser Flash Analysis (LFA) set-up used.

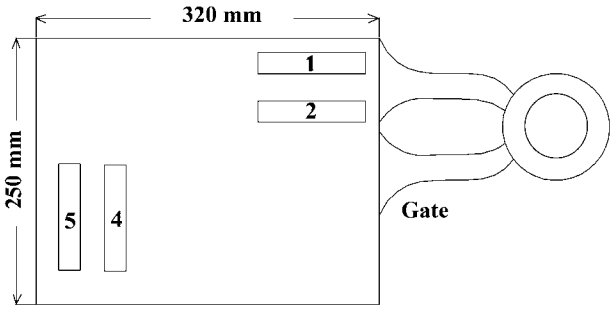

Figure 1. The rheocast component and three different tensile bars

The 6082 alloy as a commercial alloy in extrusion process was cast using conventional liquid casting in a small permanent mold for benchmarking purposes. The mold had a diameter of about 5 cm and a thickness of about 1 cm. The composition of the alloy was measured using optical emission spectroscopy and are presented in Table I. Thermal diffusivity was measured for the as cast condition using two samples. Specific heat and thermal expansion data was extracted from literatures to be able to estimate the thermal conductivity.

EDS Measurement

To understand the relation between the dissolved elements and thermal properties, samples for compositional measurment were prepared from the same position of LFA samples. The samples were polished and etched using OPS etchant. The content of main elements inside primary α_1-Al particles in rheocast samples and 6082 sample were studied under scanning electron microscope (SEM) equipped energy dispersive spectrometer (EDS). The concentrations of Si and Mn in the aluminum matrix in the as-cast state were measured using an acceleration voltage of 15kV.

Heat Treatment Procedure

Three different heat treatments were made for Alloy X to study thermal conductivity and strengths relations. The two T5 heat treatments were set as 4 h at 200°C or 3 h at 250°C. The T6 treatment consisted of a solution heat treatment at 500°C for 6 h, quench in 50°C water followed by natural ageing for 1 day. Artificial ageing was then med at 205°C for 1h (T6 205°C 1h) and 6 h (T6 205°C 6h).

Physical Properties

Thermal diffusivity was measured with a Netzsch LFA 427 laser flash apparatus. A sample diameter of 12.5 mm and a thickness of about 3.4-3.8 mm were used with a thin layer of graphite applied on the sample surfaces to maximize energy absorption. The diffusivity was measured at nine different temperatures from 30°C up to 400°C. Five measurements, with one minute intervals, were made at each temperature.

Specific heat was measured using differential scanning calorimeter (Netzsch DSC 404C). The samples were heated to 500°C and cooled at 1.5°C /min before the measurement. A sample weight of 42 mg and a sapphire standard was used. The heating rate was set to 10 K/min.

Density at room temperature was determined using *Archimedes principle*. The thermal expansion coefficient, α, was measured using a dilatometer equipment, Netzsch DIL 402C and enabling density at elevated temperatures to be calculated using Eq. 1.

$$\rho(T) = \frac{\rho(T_{RT})}{(1-\alpha(T-T_{RT}))^3} \qquad \text{Eq. 1}$$

Thermal conductivity, λ, was calculated from measurements of thermal diffusivity, a, specific heat, c_p, and density, ρ, based on Eq. 2. Thermal conductivity can be calculated as a function of temperatures by measuring a, c_p and ρ in different temperature.

$$\lambda(T) = a(T)\cdot c_p(T)\cdot \rho(T) \qquad \text{Eq. 2}$$

Mechanical Properties

The tensile test samples were extracted from 4 different position in two groups of samples from near-to-gate and near-to-vent regions, Figure 1. The samples were tested in the as cast and as-heat treated conditions. Tensile tests were performed at a strain rate of 10^{-4} /s. Strain was recorded using a Zwick™ digital clip-on extensometer with a 20 mm gauge length. The yields stress was calculated based on $Rp_{0.2}$.

Micro Vickers hardness was measured for the as cast and T6 sample before and after thermal diffusivity measurement. The applied weight was set to 500 gr for all measurement to ensure that both the α_1-Al phase and eutectic phases were included in the hardness measurement. Five indentations were made for each section.

Result and Discussion

Density and Specific Heat

Thermal expansion coefficients of Alloy X and 6082 alloy as an average value in three temperature ranges are collated in Table II. Thermal expansion in the as cast state and as-T6 treated state showed a similar results with increasing temperature. These data were used also for the evaluation of the T5 treated samples and no separate assesment was made for this state. The density of Alloy X and 6082 was measured at room temperature to 2700±10 and 2710±10 kg/m^3 respectively. The samples with density outside of the margine were eliminted due to the effect of porosity on themal conductivity. Using Eq. 1 and the thermal expansion coefficient, α, Table II, the density value were found in different temperature. The measured specific heat of Alloy X and collected date for 6082 are presented in Table III. The value of specific heat for alloy 6082 were extracted from Zahra *et al.* [13].

Table II. Thermal expansion coefficient [10^{-6}/K]

Temperature interval[°C]	Alloy X	6082
30-200	24.9	25.1
200-300	29.0	29.2
300-400	28.0	28.3

Table III. Specific heat of the 6082 alloy and Alloy X [kJ/kgK]

T [°C]	6082 [13]	Alloy X
30	0.91	0.89
50	0.93	0.90
100	0.94	0.92
150	0.97	0.94
200	0.99	0.96
250	1.00	0.98
300	1.01	1.00
350	1.06	1.02
400	1.11	1.08

Thermal Conductivity in the As-Cast Condition

Thermal diffusivity and thermal conductivity for the as-cast condition of the 6082 alloy and Alloy X are shown in Figure 3. The thermal conductivity of the 6082 alloy showed consistently lower values than Alloy X, despite its lower Si content. The high Mn content of 6082 and also the presence of Mg_2Si clusters or precipitates can be attributed to the low thermal conductivity of 6082 [8]. Mn in solid solution is known to have a large negative influence on thermal conductivity [14]. A comparative EDS measurement showed the concentration of Si was 0.5±0.09 wt.% and 0.45±0.08 wt.% in the Al phase for 6082 and Alloy X, respectively. The EDS measurement also showed that the concentration of Mn in the Al-phase was 0.41±0.06 wt.% for 6082 and 0.17±0.03 wt% for Alloy X. Similar results for Mn in 6082 with 0.54 wt.% Mn in the alloy and 0.4 wt% in the Al phase and comparable microstructure [15]. The EDS results also showed good agreement with ThermoCalc [16].

The negative influence of Mg_2Si clusters and precipitates as well as Mn on thermal conductivity should decrease with increasing temperature as a lower number density of larger precipitates should exist resulting in a reduced difference between Alloy X and 6082 should be the result. A decreased difference in thermal conductivity between Alloy X and 6082 was also observed, Figure 3. Both growth of Mg_2Si clusters and the formation of a higher fraction of Mn containing dispersoids in the 6082 alloy can thus be attributed to the decrease in difference in thermal conductivity between the 6082 alloy and Alloy X with increasing temperature.

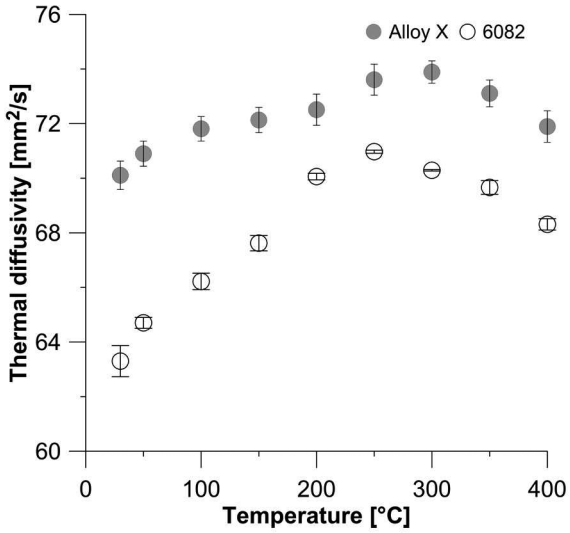

Figure 2. Thermal diffusivity of alloy 6082 and Alloy X

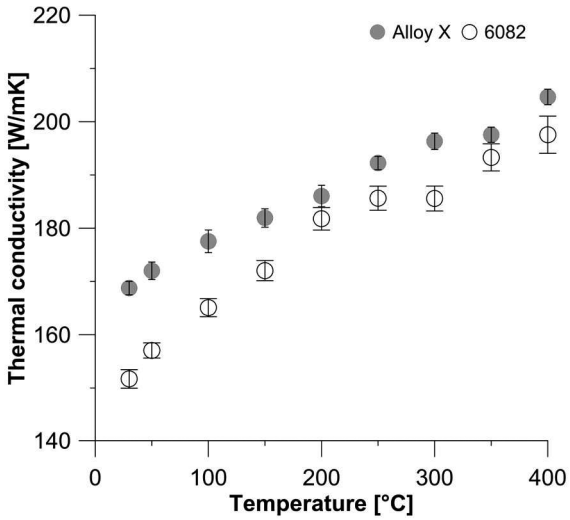

Figure 3. Thermal conductivity of alloy 6082 and Alloy X

Thermal Conductivity in the Heat Treated Condition

Figure 4 and Figure 5 shows the measured average values of thermal diffusivity and thermal conductivity for Alloy X in the as-cast, T5 and T6 heat treated states from room temperature up to 400°C. The standard deviation (STD) of the thermal conductivity values was calculated and was lower than 4 W/mK for all samples based on the standard deviation in the measurements of α, c_p and ρ. The results revealed an increase in thermal diffusivity and conductivity after heat treatment. The measurement for all samples showed the diffusivity increased and reached the higher value in the temperature range of 200°C to 250°C except the sample with T5-250°C heat treated condition. The peak in Figure 4, around 250°C, corresponds to precipitation of Si from solid solution in temperture range of 225-250°C [17]. Therefore, the Si precipitation process during T5 250°C heat treating process for 3h probably was enough to precipitate of all Si prior to measurement. In contrast, aging at 200°C resulted in incomplete process of precipitation and the remaining Si precipitated in the temperature range of 200-250°C during LFA measurement and cause increasing in the diffusivity.

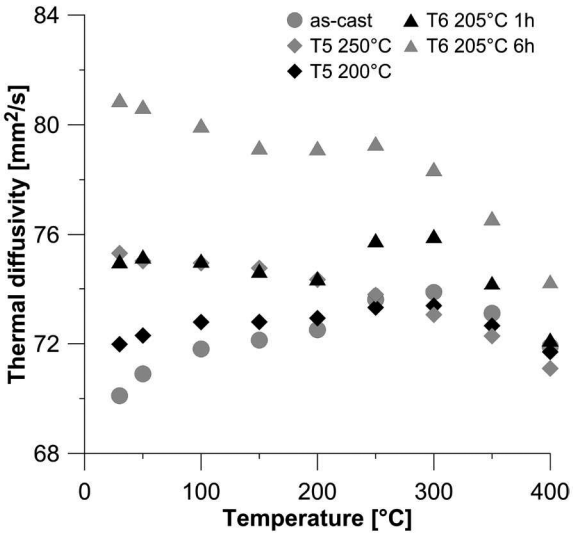

Figure 4. Thermal diffusivity for as-cast, T5 and T6 condition.

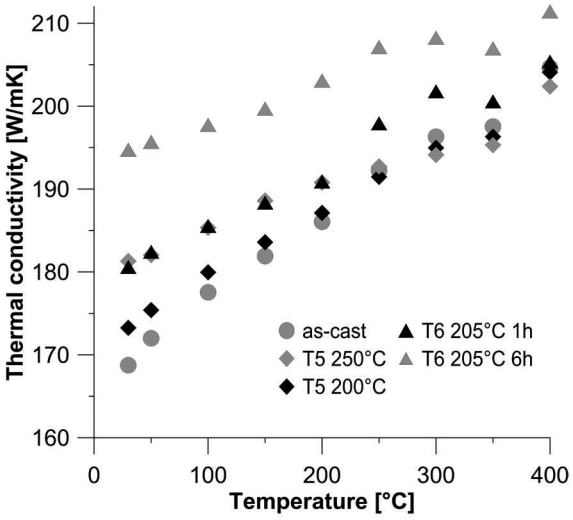

Figure 5. Thermal conductivity for as-cast, T5 and T6 condition.

T6 205°C 1h treatment increased thermal conductivity with approximately 14 W/mK. This increase improved further by artificial aging at 205°C for 6h following the T6 treatment up to a thermal conductivity of 194 W/mK. Similarly, an increase of 2.3mm^2/s in thermal diffusivity in the temperature range between 200 and 250°C for T6 205°C 1h. This should be compared to the constant diffusivity in T6 205°C 6h in the same temperature range. This clearly supports that less Si precipitated during heating process in the thermal diffusivity measurement for the T6 205°C 6h sample. Microstructural investigation before and after T6 heat treatment, Figure 6, also support this as fragmentation and sperodization of Si particles during solution treatment at temperature of 500°C can be observed. This modification results in small and rounded Si particles. Rounder Si particles results in a reduced contact area between the α-Al matrix and the Si particles [18]. Therefore, the probability for scattering of electrons by Si particles is thereby reduced, resulting in an increase in thermal conductivity. The same effect of Si morphology on thermal conductivity was reported by adding strontium as an eutectic silicon modification in A1-Si casting alloys [19]. Moreover, the effect of solution treatment in electrical conductivity between non-modified and modified alloys was studied by Closset *et al.* [20] and the results revealed that solution treatment could decrease the difference between the thermal conductivity by effecting on Si morphology. The results also showed a T5 250°C give a similar thermal diffusivity and conductivity as a T6 205°C 1h. Therefore by considering T6 treatment combined with aging process, the effect of dissolving Al_2Cu in solid solution, fragmentation of Si particles during solution treatment and also had the same effect as a T5 250°C had only by decreasing in concentration of Si in solid solution when precipitates form and grow.

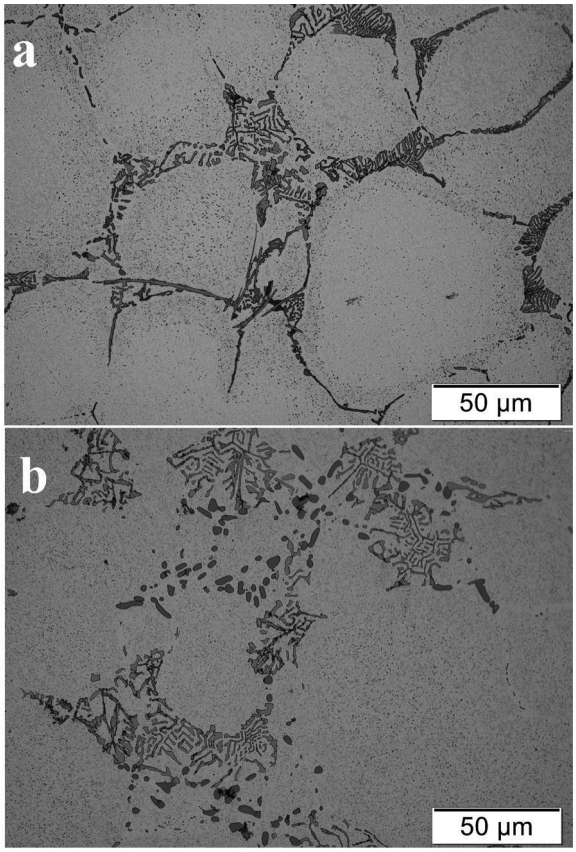

Figure 6. Microstructural features of LFA samples in (a) as cast and (b) T6 heat treatment condition

In-Situ Measurement of Thermal Diffusivity

Thermal diffusivity was also measured during the cooling cycle (5K/min from 400°C down to 20°C) for as-cast and T6 treated samples. Five measurements at 300°C, 200°C, 100°C and at room temperature were made and the results are shown in Figure 7. The results showed that thermal diffusivity at room temperature after heating the as-cast sample to 400°C and cooled down (a ten hours measurement) was higher than for the T5 250°C treatments. In addition, the T6 treated material showed a higher diffusivity at room temperature after cooling from 400°C with a thermal diffusivity of 85.7 mm^2/s corresponding to a thermal conductivity of 207 W/mK. The largest increase in thermal diffusivity was found in the as-cast samples, around 10 mm^2/s giving further support to that Si precipitation is the main cause of the effects of heat treatment on the thermal transport properties. This since the as-cast state is furthest from equilibrium with the greatest

supersaturation of Si in the matrix followed by the T5 states and the T6 state

This also indicated that thermal diffusivity could be increased further by increasing the heat treatment temperature above 250°C. One part of this increase originated from more Si precipitation and part of it is a consequence of the annealing process in the sample in the temperature range from 325°C up to 400°C. The annealing process during thermal diffusivity measurement at a sufficiently high temperature and long soaking time as well as slow cooling from the annealing temperature might relieved the residual stresses beside of Si precipitation can result in extreme thermal diffusivity [21]. On the other hand, the high thermal conductivity after annealing situation is normally accompanied by limited mechanical properties and low hardness. Vickers hardness measurements showed that the hardness was reduced by factor of 0.36, 0.33 and 0.3 for as cast, T6 205°C 1h and T6 205°C 6h respectively.

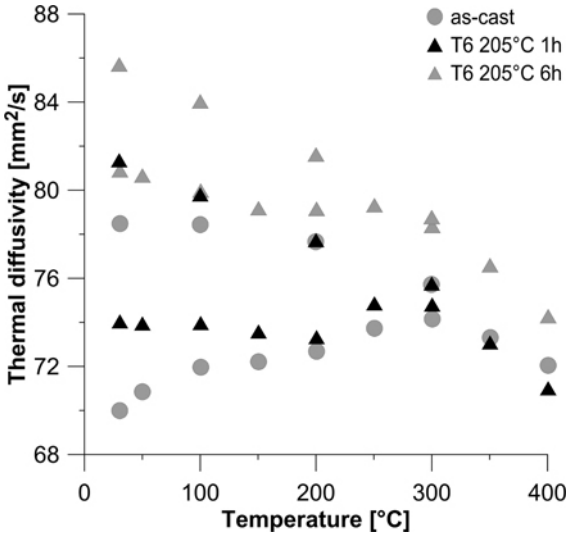

Figure 7. Thermal diffusivity of as-cast and T6 treated samples for going up to 400°C and then down to room temperature again.

Mechanical Properties

The samples for tensile testing was heat treated in different conditions. The samples number 4 from the region near-to-vent showed blistering after T6 treatment due to air entrapment during filling. The yield strength values for the tensil testing samples taken in different conditions together with the 95% confidence interval are collated in Table IV.

In as-cast condition, the yield strength for Alloy X showed slightly higher value in the samples from near-to-vent region. The finer microstructure of these samples due to concentration of more liquid portion of slurry during filling [22]. In addition, these mechanical properties for Alloy X in both solution heat treatment and artificial aging did not improve very significantly. This can be as result of absence of alloying element and mainly Mg. Ouellet *et al.* [23] investigated the effect of Mg level on heat treatability of Al-Si-Cu and recommended increasing the Mg content in the alloy up to 0.45% to enhance the alloy response to heat treatment in the T5 and T6 process. On the other hand, formation of Mg_2Si cluster can decrease thermal conductivity of final production.

Table IV-Yield Strength of Alloy X [MPa]

Condition	Near-to-gate	Near-to-vent
As-cast	64.3±2.5	69.9±2.7
T5 200°C 4h	67.6±1.6	73.4±0.8
T5 250°C 3h	67.2±2.5	72.6±1.9
T6 200°C 1h	72.1±1.3	69.4±2.1*
T6 200°C 6h	71.5±0.9	69.3±2.2*

Strength – Thermal Conductivity Relation

Figure 8 shows the relation between yield strength and conductivity as yield strength versus thermal conductivity. Compared to the as-cast state all heat treatments resulted in both an increased strength and improved thermal conductivity, primarily caused by Si precipitation. The heat treatment response in the materials showed only increase in thermal conductivity without any significant difference in yield strength. The samples from T6 205°C 6h had the best result in thermal conductivity. On the other hand, the best combination of strength and hardness was found in T6 205°C 1h and T5 250°C. Taking the risk of blistering into account, the best combination for Alloy X was the T5 250°C treatment.

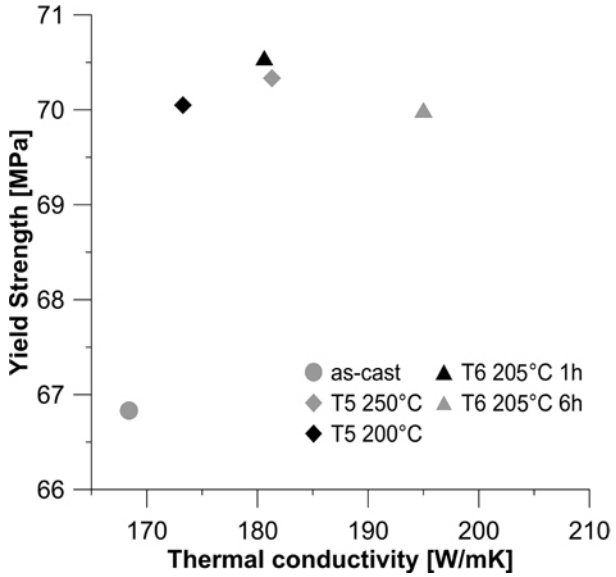

Figure 8. Relation between strength and conductivity, showing a) yield strength for rheocast samples

Conclusion

Alloy X was developed for the rheocating purpose with the aim of providing maximizes thermal conductivity for a component used in telecom industry. The alloy showed a robust behavior using the RheoMetal™ process combined with HPDC casting. Alloy X showed excellent thermal conductivity of 169 W/mK at room temperature for Alloy X in as-cast condition. Bench marking 6082 showed a lower thermal conductivity (148 W/mK) at room temperature, despite its lower Si content. EDS measurement revealed a higher concentration of Mn in solid solution in 6082 compared to Alloy X.

* Blistering were observed in the sample

Heat treatment of Alloy X showed significant improvement in thermal conductivity compared to the as-cast state. However, the mechanical properties did not significantly improve with any of the heat treatment schedules tested. The value of thermal conductivity at room temperature increased to 195 W/mK for T6 205°C 6h compared to 181 W/mK for T6 205°C 1 h. A T5 250°C 3h gave higher value than T5 200°C 1h but similar diffusivity and conductivity as a T6 treatment. The precipitation of Si was identified as the main mechanisms for the improvement in thermal conductivity. Taking blistering into account, a T5 treatment at 250°C was recommended for Alloy X giving a thermal conductivity of 181 W/mK at room temperature and maximum yield strength.

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