

FINAL TECHNICAL REPORT

Development of Elevated Temperature Aluminum Metal Matrix Composite (MMC) Alloy
and Its Processing Technology

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EXECUTIVE SUMMARY

The objective of this project was to provide a production capable cast aluminum metal matrix composite (MMC) alloy with an operating temperature capability of 250-300°C. Important industrial sectors as well as the military now seek lightweight aluminum alloy castings that can operate in temperature ranges of 250-300°C. Current needs in this temperature range are being satisfied by the use of titanium alloy castings. These have the desired strength properties but the end components are heavier and significantly more costly. Also, the energy requirements for production of titanium alloy castings are significantly higher than those required for production of aluminum alloys and aluminum alloy castings.

1.0 INTRODUCTION

Aluminum alloy castings have been successfully used in many applications to reduce weight and therefore increase fuel efficiency. Except for engine components, most of these operate at ambient temperatures. Most engine components operate at temperatures up to about 200°C.

Currently available Al-Cu and Al-Cu-Mg casting alloys have a maximum effective operating temperature of about 200°C which is equal to their aging temperature. This temperature capability is adequate for many traditional applications such as engine block and cylinder head castings for gasoline engines, and turbine compressor wheels. For example, compressor wheels for turbo-charging gasoline and diesel engines are currently produced from 354-T61 aluminum alloy castings which have a maximum operating temperature of around 175°C. Important industrial sectors, aerospace companies and the military now require lightweight alloy castings that can operate in temperature ranges of 250-300°C. Current needs in this temperature range are often being satisfied by the use of titanium alloy castings. These have the desired strength properties at temperature but the end components are heavier and significantly more costly. Also, the energy requirements for production of titanium alloy castings are significantly higher than those required for production of aluminum alloys and aluminum alloy castings. The potential replacement of alloys currently used in these temperature ranges; i.e., titanium alloys, can reduce the overall energy consumed in the manufacture of products used in this intermediate (250 - 300°C) temperature range.

The aluminum alloys demonstrating high strength at elevated temperature are primarily alloyed with copper and other additions to form intermetallic precipitates that increase alloy strength and hardness. The major strengthening phases of these alloys are θ' (Al_2Cu) and S' (Al_2CuMg). Above a metal temperature of about 230°C these strengthening precipitates rapidly coarsen or dissolve, and transform into the more stable θ (Al_2Cu) and S (Al_2CuMg) phases. These transformations reduce coherency with the matrix resulting in a dramatic reduction of mechanical properties, most specifically ultimate tensile strength and high cycle fatigue strengths. It is well known that the incorporation of ceramic particles, particularly of sizes in the range of five to ten microns will improve the high temperature properties of aluminum alloys. The technical risk of these approaches is that the resulting alloys are difficult to manufacture and/or difficult to cast.

2.0 BACKGROUND

2.1 OBJECTIVE OF DEVELOPMENT PROGRAM

The objective of this research was to develop a castable aluminum alloy metal matrix composite (Al MMC) system containing thermally stable particles that increase tensile and fatigue strength at elevated temperatures (250°C to 300°C). The strengthening phases in this elevated temperature capable castable aluminum alloy must have long term - greater than 1000 hours - stability at temperature.

2.2 STATE OF CURRENT TECHNOLOGY

The high temperature performance of aluminum alloys may be enhanced by any one of or a combination of the following three methods; precipitation hardening, addition of thermally stable ceramic particles, and solid solution strengthening. The first approach involves the in-situ formation of very fine thermally stable intermetallic phases in the aluminum matrix that will not coarsen at elevated temperatures. The second approach is the addition of small ceramic particulates to an aluminum matrix alloy thus creating a metal matrix composite (MMC). In the third approach, elements which show complete solubility in the solid state are added to increase the yield and tensile strengths of the solvent, in this case pure aluminum. In the current project our focus was the development of a castable metal matrix composite (MMC) consisting of a matrix alloy precipitation hardened by thermally stable intermetallic phases. Further enhancement of elevated temperature properties would be accomplished by the addition of a modest quantity of micron-sized ceramic particles. Our experience with the commercially available aluminum MMC casting alloys has taught us that minimizing the volume of ceramic particles added maintains alloy castability.

Precipitation Hardened Alloys. The in-situ formation of thermally stable phases is widely known and extensively used for various alloy systems, known as precipitation-strengthened alloys. There are few Al-Cu and Al-Si casting alloys specified in the ASM Metals Handbook which fall under this category and could be used for high temperature applications [1].

The major task in the development of a new alloy system is to ascertain the thermal stability of candidate strengthening precipitates and then devise an alloy that contains the stable precipitates

that increase ultimate tensile and fatigue strengths at elevated temperatures (250-350°C). The addition of Ni, Co, and Zr to essentially an A206 composition results in the Rolls Royce alloy 350 that has increased temperature properties but exhibits poor castability [2].

Al-Cu casting alloys, for example A201 and A206, are strengthened by the intermetallic precipitates such as Al_2Cu and Al_2CuMg formed during heat treatment and retain their strength up to a temperature of 200°C. However, above 230°C these precipitates coarsen or dissolve rapidly. It has been shown that these transformations reduce coherency with the matrix resulting in a dramatic reduction of mechanical properties, most specifically ultimate tensile strength and high cycle fatigue properties.

The second group of aluminum alloys used for high temperature applications are Al-Si alloys [3-8]. Several aluminum-silicon-copper hypereutectic and eutectic alloys used to manufacture cast aluminum engine pistons contain additions of Ti, Zr, V, Cr, etc. to improve both intermediate and elevated temperature properties [3, 4]. These alloys provide adequate tensile and yield strengths at temperatures up to 350°C but have insufficient fracture toughness to be considered for structural (fatigue driven) applications. The addition of even higher quantities of V and Zr, in a recent NASA alloy, has shown that the operating temperature can be increased by another 75°C to 100°C over those already available [3]. These alloys appear to be promising but there is some question as to whether the alloys will have sufficient fracture toughness to be used for applications which demand excellent fatigue performance at elevated temperatures.

Granger et al reported the development of a hypereutectic aluminum-silicon alloy, C56F having the following composition Al-15.6%Si-0.62%Fe, 4.8%Cu-0.62%Mg-5.2%Ni-0.04%Ti-0.005%P. This alloy has improved tensile properties in the temperature range 315-370C (600-700F) a requirement for piston applications [4]. The fatigue behaviour of this alloy is not available.

Crepeau et al reported improved tensile and high cycle fatigue (HCF) properties at elevated temperatures (177 and 343°C) of test samples sectioned from a cast diesel piston from a near-eutectic Al-Si alloy 339-T5, containing Cu, Mg and Ni. The improved properties at elevated temperatures were associated with the formation of CuAl_2 and Mg_2Si intermetallics that strengthen the matrix after artificial aging [5]. Hence the challenges for precipitation hardened alloys approach

include: (a) the selection of alloy chemistries that provide chemically stable intermetallic precipitates that strengthen at elevated temperatures (greater than 300°C) and have morphologies that are not detrimental to fracture toughness properties, and (b) the assurance that the resultant alloy system can be cast into high quality components using cost effective production methods.

It is known that many trialuminide particles including Al_3Ti , Al_3Y , Al_3Zr and Al_3Hf are stable at high temperatures [9]. However, most of these binary trialuminide particles are brittle and lack coherency in many aluminum alloys making them unsuitable as strengthening elements. Scandium is reported to form a ductile, coherent Al_3Sc particle in various aluminum alloys including Al-Mg, Al-Zn-Mg and Al-Mg-Li systems. These coherent particles contributed to the high temperature stability by increasing the recrystallization temperature.

Scandium cannot be used with all alloying elements. It is mentioned in the literature that Sc can form W-phase particles when the Cu-Sc ratio exceeds certain limits [10-14]. An estimate of the Cu and Sc contents that may preclude the formation of W-phase particles was plotted using the data from literature. This plot (Figure 1) predicts the allowable Sc content of aluminum copper alloys if the formation of 'W' phase is to be prevented. These reactions cause particles to grow in the melt that consume copper and scandium making these solutes unavailable to form stable Al_3Sc precipitates during heat treatment. Similarly, it has been reported that silicon can react with scandium to form primary precipitates making hardening impossible. Work done by Yu et al., [13] showed that the addition of 0.3% Sc and 0.3% Zr to an aluminum alloy containing 2.2% Cu (the other elements were similar to aluminum alloy 2618) had a positive response to aging. Also elevated temperature mechanical properties of this alloy were improved. In the current work effect of scandium on the mechanical properties of an Al-Cu alloy designed for casting was evaluated.

Metal Matrix Composites. The second approach constitutes the fabrication of an aluminum metal matrix composite. A good example of this technology is the addition of micron sized SiC particles to an aluminum alloy such as 359.0 using the stir casting process. Conventional casting processes can be used to manufacture complex components. It has been reported that by adding ceramic fibers to a eutectic Al-Si casting alloy the operating temperature of the alloy can be increased by as much as 100°C [11].

The challenges of the metal matrix composite approach include: (a) the selection of a ceramic or intermetallic reinforcement that is chemically stable at elevated temperatures in an aluminum matrix that does not contain silicon, (b) devising a low-cost, liquid-metal mixing technology that can homogeneously incorporate fine (5 to 8 micron diameter) particulates into an aluminum alloy matrix having good elevated temperature mechanical properties, and (c) the assurance that the resultant alloy system can be cast into high quality components using cost effective production methods.

Solid Solution Strengthened Alloys. Solid solution strengthening is extensively used for wrought aluminum alloys. These alloys contain Mg, Cr or Mn as the major alloying elements and most of these alloys are non-heat treatable.

2.3 TECHNICAL APPROACH

Our selected approach was the addition of small, thermally stable ceramic particulates to an Al-Cu--X matrix alloy. The challenges for this approach included:

1. Development of an Al-Cu-X matrix alloy that contains strengthening precipitates that are thermally stable at operating temperatures greater than 250°C and is castable with conventional casting processes.
2. Selection of a commercially available ceramic or intermetallic reinforcement particle that is chemically stable at operating temperatures greater than 250°C in an aluminum matrix that does not contain silicon.
3. Devising a low-cost, liquid-metal mixing technology that can homogeneously incorporate fine (5 to 8 micron diameter) particulates into an aluminum alloy itself having good elevated temperature mechanical properties, and
4. Assuring that the resultant alloy system may be cast into high quality components using cost effective production methods.

A two-phase program plan was devised and executed to meet the established project objective – the development of a castable aluminum alloy capable of operational temperatures greater than 250°C. The alloy system (matrix and ceramic reinforcement) must have both the desired properties and the ability to be cast into near-net or net shape components.

Phase I – Design and Development of Al-Cu-X MMC Alloy System - was designed to develop aluminum alloy matrix chemistry and determine a compatible ceramic particulate reinforcement that provides the desired elevated temperature mechanical properties.

The Phase II effort – Development of Manufacturing Technologies - established the manufacturing technologies necessary to utilize the new elevated temperature capable alloy system for the production of commercial castings and determined the alloy's static and dynamic mechanical properties. As development proceeded, contacts with potential users established a need for the prototype production of demonstration castings to more firmly establish the alloy systems castability and mechanical properties attainable in “real life” components. In the same time frame, it became apparent that to use the new alloys for commercial applications commercial specifications would be required.

The tasks devised and executed to meet the objectives of this project were:

1.0 Phase 1 – Design and Development of Al-Cu-X MMC Alloy System

1.1 Development of Al-Cu-X Matrix Alloy

1.1.1 Matrix Alloy Development

- a. Consultation with experts
- b. Statistically based alloy experiments
- c. Selection of potential alloy chemistries

1.1.2 Matrix Alloy Property Evaluation

- a. Preparation of alloys & casting of test samples
- b. Property evaluation – hardness & tensile strength
- c. Microstructural evaluation
- d. Selection of matrix alloy composition

1.2 Development of Al-Cu-X MMC Alloy

1.2.1 Selection of reinforcement particle chemistry

- a. Chemistry
- b. Particle coating chemistry
- c. Single fixed volume fraction

- 1.2.2 Preparation of MMC test samples and evaluation
 - a. Casting of tensile test samples
 - b. Long term exposure at test temperatures
 - c. Microstructural analysis for interface reactions, etc.
 - d. Property evaluation – hardness & tensile strength
- 1.2.3 Selection of MMC alloy systems (2 max)

1.3 Evaluation of Selected MMC Alloys

- 1.3.1 Preparation of tensile test samples
 - a. Casting of tensile specimens; 5 to 10 pound melts
 - b. Long term exposure at test temperatures.
- 1.3.2 Evaluation of Properties
 - a. Tensile testing at room & elevated temperatures
 - b. Microstructural analysis for interface reactions, etc.
- 1.3.3 Selection of MMC alloy system

2.0 Phase 2 – Development of Manufacturing Technologies

- 2.1 Develop Clean Melting and Mixing Practices
- 2.2 Develop Casting Process Parameters
- 2.3 Evaluate Mechanical Properties of Al-Cu-X Matrix Alloy and Al-Cu-X MMC Alloy
 - 2.3.1 Room temperature tensile and fatigue properties
 - 2.3.2 Elevated temperature tensile and fatigue properties
 - 2.3.3 Determine thermal expansion coefficients
- 2.4 Produce Demonstration Castings (partially funded by customers)
- 2.5 Write and Submit Draft Alloy Specifications to SAE AMS

3.0 RESULTS AND DISCUSSION

3.1 PHASE 1 - DESIGN AND DEVELOPMENT OF AL-CU-X MMC ALLOY SYSTEM

This phase of the technical effort alloy was accomplished by CANMET Materials Technology Laboratory under contract to Eck Industries. The experimental effort was divided into two (2) Tasks. Under the direction of Eck Industries technical project manager Task 1, Matrix Alloy Development, was accomplished by M. Sadayappan, J.P. Thomson, R. Zavadil and M. Sahoo and Task 2, MMC Alloy Development was accomplished by M. Popescu, R. Zhang, R. Santos, V. Guertsman and J. Lo

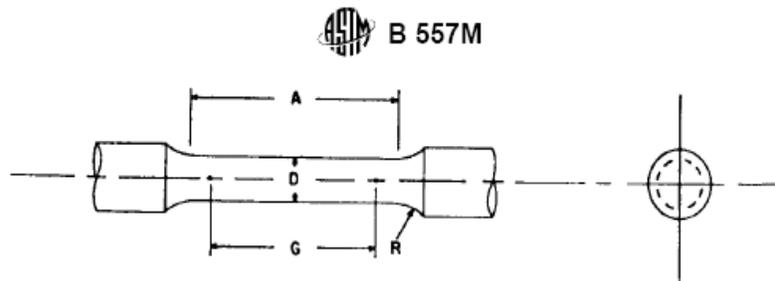
3.1.1 Al-Cu-X Matrix Alloy Development

Development Plan. As a result of information exchange with various alloy development experts in the aluminum industry, Universities and research organizations it was determined that aluminum alloy A206 based on the Al-Cu-Mg system was the best candidate alloy system for development of an elevated temperature capable matrix alloy. The Al-Cu alloy system was chosen as the base alloy for the experiments because of its room temperature strength. Further review of the literature on the development of high-temperature aluminum alloys suggested that the addition of Sc and/or Zr may form nano-scale tri-aluminide particles in the alloy that are stable at temperatures up to 400°C. Creep resistance is significantly enhanced by the presence of the $Al_3(Sc, Zr)$ particles^(15, 16). Thus, only systems containing Sc or Zr were selected for the final investigation. Also the amount of Sc was restricted to 0.3% and the maximum amount of zirconium added was 0.04%.

To reduce development time and cost, the effectiveness of the various experimental parameters during the optimization of the alloy composition and thermal treatment cycles were initially measured by use of Brinell hardness measurements. These tests were conducted using 500 kg load. Subsequent tensile tests were accomplished after optimization of heat treatment parameters. Tensile test samples having the dimensions shown in Figure 1 were prepared from permanent mold cast plates. Testing was done at room temperature and 250°C.

Experimental Details: Casting Trials. A 100 kW push up type induction furnace was used for melting. Either A206 ingots or pure aluminum was used as the starting material for preparing the alloys. Alloying additions were made as master alloys or pure metals. Master alloys used in this work were Al-33% Cu, Al-2% Sc, Al-25% Ni, and Al-33% Mn. Magnesium and silicon were added as pure metals.

In each experiment 20kg of selected alloy was prepared. The ingots and selected master alloys were charged into a clay graphite crucible and melted in an induction furnace. The melt was degassed using C_2Cl_6 tablets due to the small melt sizes. Magnesium and Scandium (as Al-Sc master alloy) were added after degassing. The composition of the alloy was determined using an optical emission spectrograph before casting operation. Most of the melts were designed as split melts where extra alloy additions were carried out after the first set of experiments. The final composition was evaluated by wet chemical analysis using the ICP method. Permanent mold cast plates (150 x 100 x 12.5 mm) or rods (19 mm diameter) were produced to obtain test coupons. In all fifteen (15) alloys were prepared in this investigation (see Table 2).



G – 45 mm; D-9 mm; R-8 mm; A-64 mm; Total length 144 mm;
Grip Length -40 mm; Grip Diameter -16.5 mm

Figure 1: Dimensions of the Tensile Test Specimens.

Experimental Details: Heat Treatment. Initially, the heat treatment cycles used to evaluate the experimental melts were knowledge based and not optimized for each specific alloy. This is due to the fact that precipitation and growth of Al_3Sc and Al_3Zr occur at higher temperatures than Cu_2Al precipitation. Because the diffusion rate of Cu in Al is slow a two stage solution heat treatment cycle and aging was necessary. On the other hand the ageing treatment was selected based on the precipitation of trialuminides containing Sc or Zr as explained below. The heat treatment parameters used for each alloy are presented in Table 1.

Heat Treatment of Scandium Containing Alloys

- Most of thermal processing work had been on pure aluminum and Al-Mg wrought alloys containing scandium. But very little information for copper containing cast alloys.

- The maximum solubility of Sc in aluminum is 0.38% by weight at 660°C. To maximize the formation of Sc trialuminides, the Sc present in the alloy must be taken completely into solution and quenched as rapidly as possible to maximize the amount of Sc in solid solution.
- The heat treatment cycles discussed in the literature deal primarily with Al-Sc and Al-Mg-Sc alloys. These data, including those from Northwestern University cannot be used as they involve very high solution temperatures in the range above 600C. At this temperature Al-4.5% Cu alloys suffer from grain boundary melting.
- The ageing of Al-Cu-Sc alloys needs to be accomplished in the 250° to 300°C to prevent grain boundary melting.

Heat Treatment of Zirconium Containing Alloys

- Zr containing alloys need to be aged in the range of 400° – 450°C to form the Zr trialuminides.
- Intermediate aging temperatures may be used for alloys containing both Zr and Sc.

Table 1: Heat Treatment Parameters

Alloy #	Annealing	Solution Treatment		Quench	Ageing	
		Temp, °C	Time, hrs		Temp, °C	Time
1	490C - 2hr	525	14	Warm water; 65°C	210	8 hrs
3	490C - 2hr	525	14		400	1 - 10 hrs
7	490C - 2hr	525	14		400	1 - 10 hrs
8	490C - 2hr	525	14		300	1 - 10 hrs
9	490C - 2hr	525	14		300	1 - 10 hrs
10	490C - 2hr	525	14		300	15 min, 1-10hrs
11	490C - 2hr	525	14		300	15 min, 1-10 hrs
12	490C - 2hr	525	14		300	15 min, 1-10 hrs
13	490C - 2hr	560	4		300	15 min, 2, 6 hrs
13a	490C - 2hr	590	4		300	15 min, 2, 6 hrs
14	490C - 2hr	560	4		300	15 min, 2, 6 hrs
14a	490C - 2hr	590	4		300	15 min, 2, 6 hrs
15	490C - 2hr	560	4		300	15 min, 2, 6 hrs

15a	490C - 2hr	590	4		300	15 min, 2, 6 hrs
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Experimental Results. As mentioned in the experimental details section 15 alloys were prepared. The final compositions of all alloys are reported in Table 2. In the discussion part report the alloys will be referred using Alloy number mentioned in this table. Based on the composition these alloys can be divided into three groups as explained below. Discussion of the results will be based on individual groups.

Group 1 (Alloys 1 – 9): These alloys contain more than 2.5% copper, magnesium with zirconium or scandium.

Group 2 (Alloys 10-12): These alloys contain lower copper content of 2 to 2.2%. Other elements such as magnesium, silicon, nickel, scandium and manganese were added in various levels.

Group 3 (Alloys 13 – 15): The last set of alloys contains copper content of 2%. These alloys also contain various amounts of silicon, nickel, manganese and magnesium. Scandium or zirconium were added to these alloys

Table 2: Composition of the Experimental Alloys

Alloy Number	Cu	Mg	Si	Ni	Mn	Sc	Zr	Other
1	5.10	0.35						
2	5.00	0.36					0.260	
3	5.10	0.38					0.427	
4	4.34	0.28				0.181		0.171 Ti
5	4.40	0.29				0.341		0.156 Ti
6	2.71	0.18				0.339		0.101 Ti
7	2.48	0.17					0.265	0.117 Ti
8	2.68	0.17				0.167	0.157	0.11 Ti
9	3.97	0.20				0.166	0.160	0.111 Ti
10	2.20		0.43	0.47	0.48	0.25		
11	2.20		0.78	0.46	0.47	0.245		

12	2.00	0.84	0.80	0.47	0.46	0.245		
13	1.99	0.98	0.47	0.55	0.23	0.17		
14	2.00	0.94	0.45	0.56	0.23	0.17	0.02	
15	1.91	0.92		0.52	0.48	0.16		

Optimization of Composition and Heat Treatment

The first task was to optimize the composition which has good mechanical properties. Due to the reason that many alloys were tested, hardness was the property chosen to identify optimum composition and heat treatment. As mentioned above the discussion will be divided into three sections.

Group 1. The nine alloys in this group contain 2.5% or higher copper. The Cu content in these alloys and the presence of magnesium dictates that a two-step solution heat treatment be used; 490°C for 2 hours plus 525°C for 14 hours, followed by quenching into 65°C water. The ageing treatment was selected based on the expected precipitates. The base A206 alloy (alloy 1) was aged at 210°C for eight hours according to standard industry T7 heat treatment practice. The ageing treatment used for the alloys containing both Zr and Sc (alloys 8, 9 & 14) was designed based on data extracted from the open literature. Because the precipitation of $Al_3(Sc, X)$ occurs in the temperature range of 275°C to 325°C, the alloys containing Sc were aged at 300°C. Since Al_3Zr is precipitated in the range 375°C to 425°C, the alloys containing only Zr (alloys 2, 3 & 7) were aged at 400°C.

Only five alloys from this group, Alloys # 1,3,7,8 and 9, were selected and subjected to heat treatment. The hardness of these alloys in various thermal treatments is reported in Table 3. The results indicate that:

- The hardness in the as-cast condition reflects the effect of copper content in the alloy. Alloys 1 and 3 have higher hardness compared to alloys 7, 8 and 9. The first two alloys have higher copper content.
- Alloys 1 and 3 exhibit improved hardness after solution treatment. This is due to complete dissolution of copper in the matrix which increases the hardness. The other three alloys have no improvement in hardness after solution treatment.

- The hardness of alloy 1 improves after solution treatment and aging. The hardness of 102 BHN represents the overaged (T7) condition of alloy A206.
- The addition of Zr (alloy 3) to A206 alloy resulted in a significantly decreased hardness after ageing. The final hardness after ageing treatment is much lower than the as-cast hardness.
- The hardness of other three alloys (7, 8 and 9) alloys improves after ageing treatment. However all the four experimental alloys exhibit very low hardness compared to the base alloy itself.
- Hardness can be converted empirically to yield strength and this experiment indicates that the four new alloys have much lower strength than the base alloy even after solution treatment.

Table 3: Effect of Group 1 Alloy Chemistries and Heat Treatment Parameters on Hardness (Strength).

Alloy Number	As Cast BHN	Solution Treated BHN	BHN After Aging for x hours											
			0.25 hr	1 hr	2 hr	3hr	4 hr	5 hr	6 hr	7 hr	8 hr	9 hr	10 hr	
1	74	89		-	-	-	-	-	-	-	-	102	-	-
3	77	90		73	71	69	68	67	66	63	68	62	58	
7	50	51		63	59	56	56	53	52	56	60	53	59	
8	52	54		62	65	63	64	61	63	66	60	63	64	
9	67	66		74	76	74	74	77	75	79	74	78	76	

These results suggested that solution heat treatment times used for the alloys containing Zr and Sc were too short. Literature reports longer soaking times for alloys containing Sc and Zr [12]. Experiments to evaluate the effect of solution heat treatment times were conducted by increasing the hold times at 525 °C to 24, 48 and 96 hours for two alloys. However, no change was observed in the response of alloys to aging as shown in Table 4. In fact longer holding times reduced the final hardness indicating the softening of matrix. Microstructural evaluation (Figure 2) indicated that the Sc is tied up in Al-Cu-Mg eutectic particles located in the grain boundaries. Thus, the Sc is not available to form the trialuminide precipitates that enhance elevated temperature strength.

Table 4: Effect of Solution Times on Hardness (Strength).

Solution holding time, hrs	BHN after aging At 300°C for 5 hrs	
	Alloy 8	Alloy 9
14	71.5	79.6
24	69.1	77.9
48	65	76.8
96	64.6	75.7

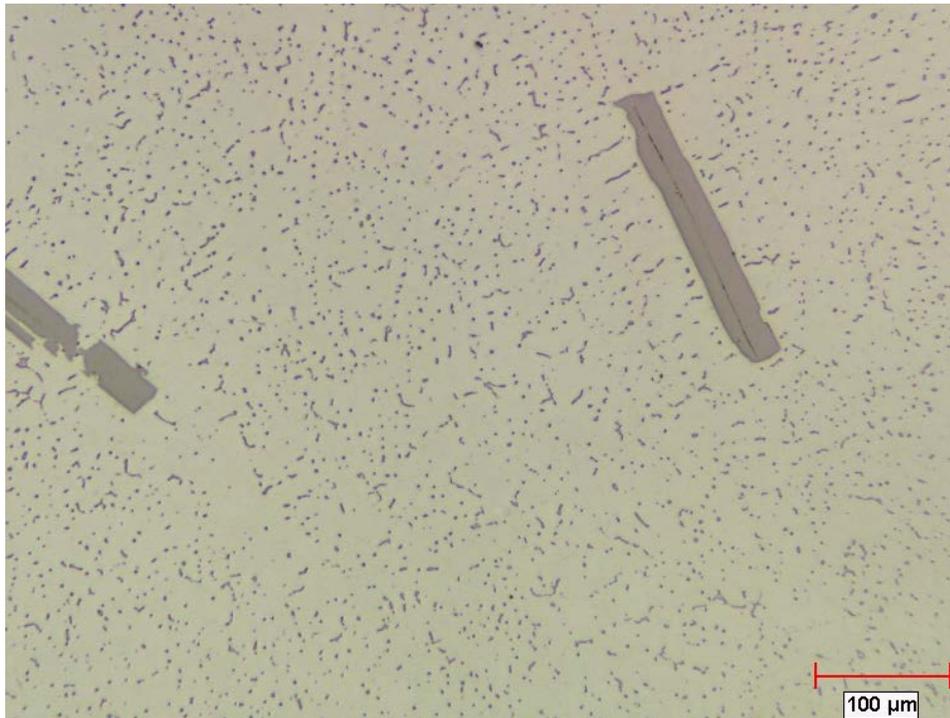


Figure 2: W - Phase in Al-Cu-Mg Alloy 5

As mentioned in the literature [13, 14] Sc can form W- phase particles when the Cu-Sc ratio exceeds certain limit. An estimate of the Cu and Sc contents that may preclude the formation of W-phase particles was plotted using the data from literature. This plot (Figure 3) predicts that for a Sc content of 0.23% the Cu content should not exceed 2.6%.

Work done by Yu et al showed that the addition of Sc and Zr to an aluminum alloy containing 2.2% Cu (the other elements were similar to alloy 2618) had a positive response to aging and elevated temperature mechanical properties were improved [13]. This suggests that the Sc was in solution when the Cu level in the alloy did not exceed 2.2%.

Group 2. The results for the Group 1 alloys indicated that the copper content was too high. This result is in agreement with the data available in the literature. Hence it was decided to restrict copper content to 2.2%. Casting fluidity of Al- Cu-Mg alloys is generally low. To enhance the casting fluidity it was decided to add small amount

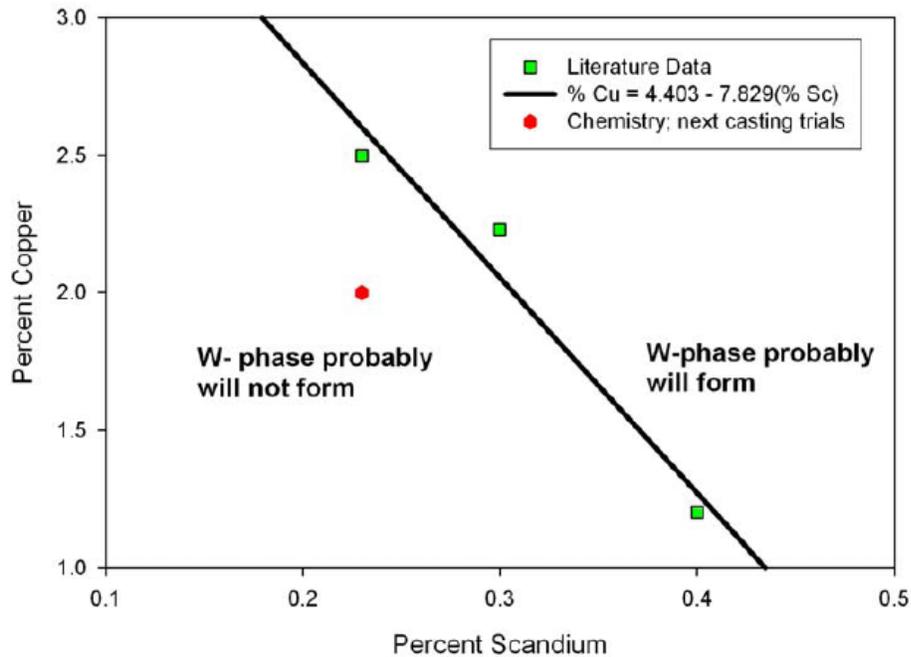


Figure 3: Relation between Copper and Scandium Content on the Formation of W-Phase Precipitates.

of silicon. Literature indicates that there are no known interactions between Si and Sc [16] when the silicon content is very low. Two levels of silicon content were examined in this investigation. Also the magnesium content of these alloys was increased from 0.35% to 1.0%. Nickel was added to the alloy to improve the solid solution strengthening. This composition, except for the lower copper content, is very similar to the wrought aluminum alloy 2618. All these alloys were solution treated at 525°C and aged at 300°C. The hardness results are presented in Table 5. The hardness test results indicate the following:

- Alloys 10 and 11 have very low hardness in as-cast condition. On the other hand alloy 12 has very high hardness. This is due to the effect of magnesium which provides high solid solution strengthening.
- After the solution treatment all three alloys exhibit softening.
- The ageing treatment improves the hardness of alloys 10 and 11 significantly. However even after 10 hrs of heat treatment the alloys are still much softer than the base alloy 1.
- Hardness of alloy 12 exhibit a peak at shorter ageing time which rapidly decreases as the ageing time is increased. The final hardness of the alloy is very similar to that of the as-cast base alloy.

Table 5: Effect of Si & Mg on Hardness (Strength) Values.

Alloy No.	As Cast, BHN	Solution Treatment, hrs	BHN after aging at 300°C										
			15 min	1 hr	2 hr	3h r	4 hr	5 hr	6 hr	7 hr	8 hr	9 hr	10 hr
10	62	48	57	61	62	63	63	64	63	65	66	64	65
11	59	53	56	57	58	57	57	58	60	62	57	54	57
12	81	68	101	77	73	68	68	71	69	71	67	68	71

The positive response of these three alloys to thermal treatment is shown in Figure 4. As it can be observed the best performance is that of Al-Cu-Mg-Sc alloy. However the final hardness observed is very low. One possibility for the very low hardness is unavailability of Sc for precipitation during ageing treatment. The solubility of Sc in aluminum increases with solution temperature and reaches 0.2% at 600°C. Initially solution heat treatment in this investigation was restricted to 525°C due to the higher copper content. Hence it was decided to reduce the copper content to less than 2% and maintain all other elements at the same levels. With this composition it is possible to solution heat treat at higher temperatures.

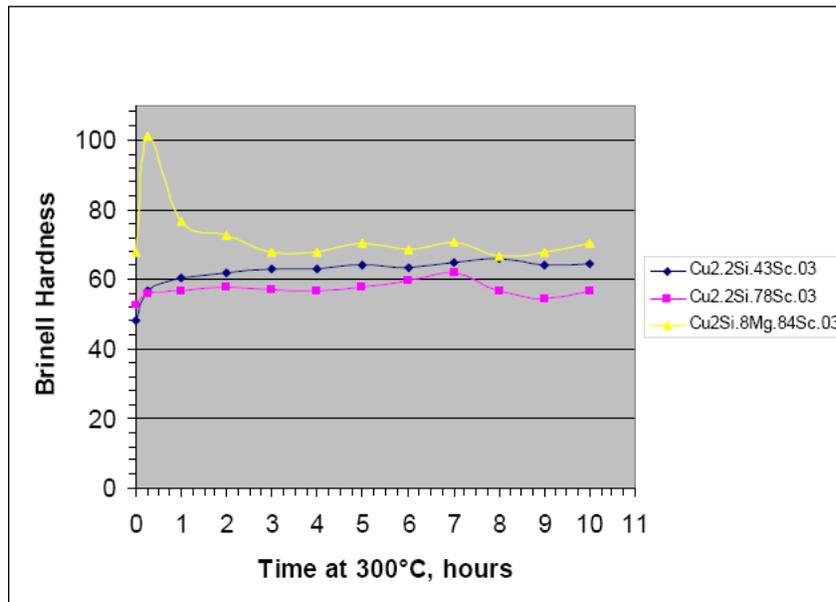


Figure 4: Ageing Response of Alloys Containing 2.2 w/o Copper

Group 3. The Cu content of the Group 3 alloys were reduced to 2% to enable the use of higher solution heat treat temperatures. Alloys 13 and 14 had essentially the same chemistry with the exception of a small amount of Zr added to alloy 14. Alloy 15 contained Mn instead of Si. The alloys solution treated at 560°C were designated as 13, 14 and 15. The alloys solution treated at 590°C were designated as 13a, 14a and 15a. After this high temperature solution treatment these alloys were aged at 300°C. The hardness test results (see Table 6) indicate the following:

- As cast hardness values of these alloys are higher than that of base A206 alloy. This is due to the presence of magnesium and nickel which provide solid solution strengthening.
- Solution treatment at 590°C results in alloys with softer matrix compared to those alloys solution treated at 560°C.
- Hardness of the alloys 13 and 14 always increase after ageing treatment; the increase in hardness is not very significant for alloy 15.
- Hardness reaches a peak just after 15 minutes of ageing treatment for alloys 13 and 14. Longer holding times result in reduced hardness.

The response of alloys 10, 12, 13 and 14 to ageing treatment is shown in Figure 5. Alloy 13a is much more stable than the other alloys. Even though the initial hardness of alloy 13a is lower compared to other alloys, the hardness is higher after 6 hours of ageing and it stabilizes more rapidly. Similar trend was seen for alloy 14a.

Table 6: Effect of Revised Chemistry and Solution Treatment Temperature on Hardness (Strength).

Alloy Number	As Cast BHN	Solution Treated BHN	BHN after Ageing		
			15 min	2 hr	6 hr
13	83	77	113	90	77
13a	83	56	96	90	84
14	88	78	118	90	76
14a	88	57	96	91	81
15	79	83	76	79	77
15a	79	81	82	79	80

Effect of Long Term Exposure. The next step was to evaluate the effect of long term exposure at 250°C on the properties of the candidate alloys. Each of the alloys was thermally treated using the parameters previously discussed. Samples were exposed in air for 100, 250 and 1000 hrs. The hardness values of the samples are reported in Table 7 and plotted in Figure 6.

The results indicate that alloys 13a and 14a retain their hardness even after holding at 250C for 1000 hrs. All other alloys exhibit softening at various levels. The alloy 14a contains a small amount of zirconium and it is known that Zr containing precipitates are thermally stable in aluminum alloys up to about 375°C. Because of the small amount of Zr present It is not expected that the higher stability of this alloy is due only to zirconium precipitates. The higher stability of this alloy can be attributed to scandium trialuminides. It was decided to determine room temperature and 250°C tensile properties of the two alloys showing the best hardness retention after elevated temperature exposure; alloys 13a and 14a.

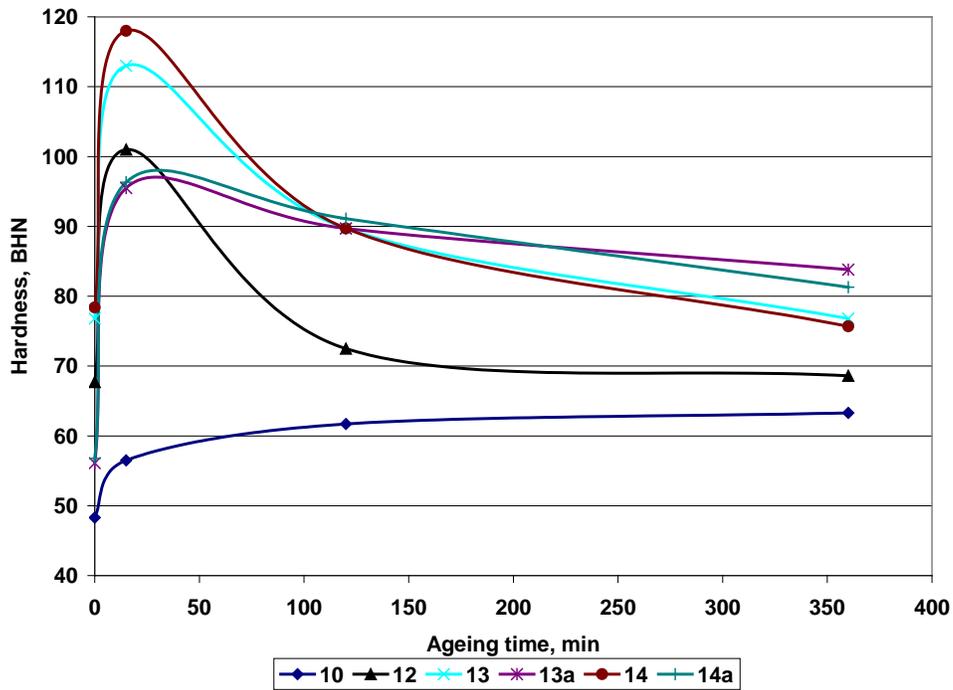


Figure 5: Ageing Response of Alloys at Different Solution Temperatures.

Table 7: Effect of Long Term Exposure at 250°C on Hardness.

Alloy	As Cast HRB	Solution Treated HRB	Aged, 6 hrs	Exposed, 1000 hr at 250° C
10	62	48	63	62
11	59	53	60	57
12	81	68	69	60
13	83	77	77	71
13a	83	56	84	80
14	88	78	76	69
14a	88	57	81	78
15	79	83	76	75
15a	79	81	80	75

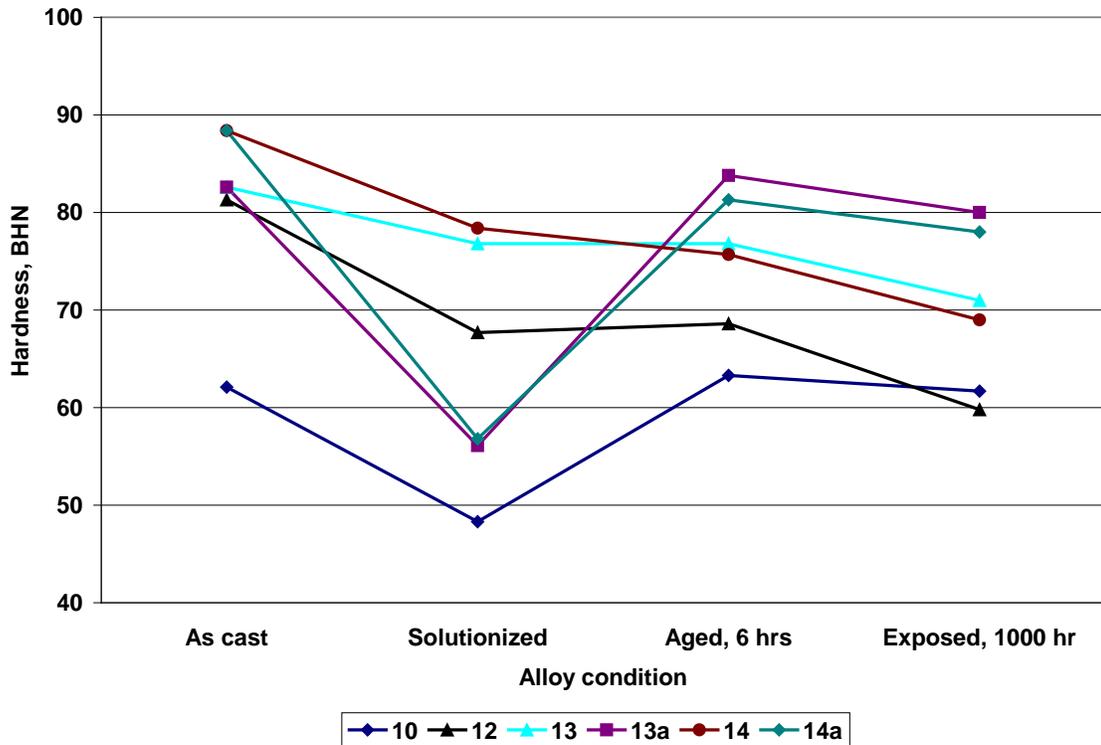


Figure 6: Hardness of Alloys after Long Term Exposure at 250°C

Tensile properties

Tensile testing was conducted for alloys 13a and 14a only. Heat treated test bars were soaked at 250°C for 100, 500 and 1000 hrs before testing. Tensile testing was carried out room temperature and 250°C. The test specimens contained considerable amount of porosity. Only yield strength data were obtained and the specimens fractured immediately after that. Hence only yield strengths are reported here. Results are presented in Table 8 and plotted in Figure 7.

Table 8: Effect of Long Term Exposure in air at 250°C on Yield Strength.

Alloy	Heat Treated MPa		100 hr Exposure MPa		500 hr Exposure MPa		1000 hr Exposure MPa	
	@ RT	@ 250°C	@ RT	@ 250°C	@ RT	@ 250°C	@ RT	@ 250°C
13a	245	199	180	139	157	108	159	105
14a	219	205	176	150	143	104	150	105

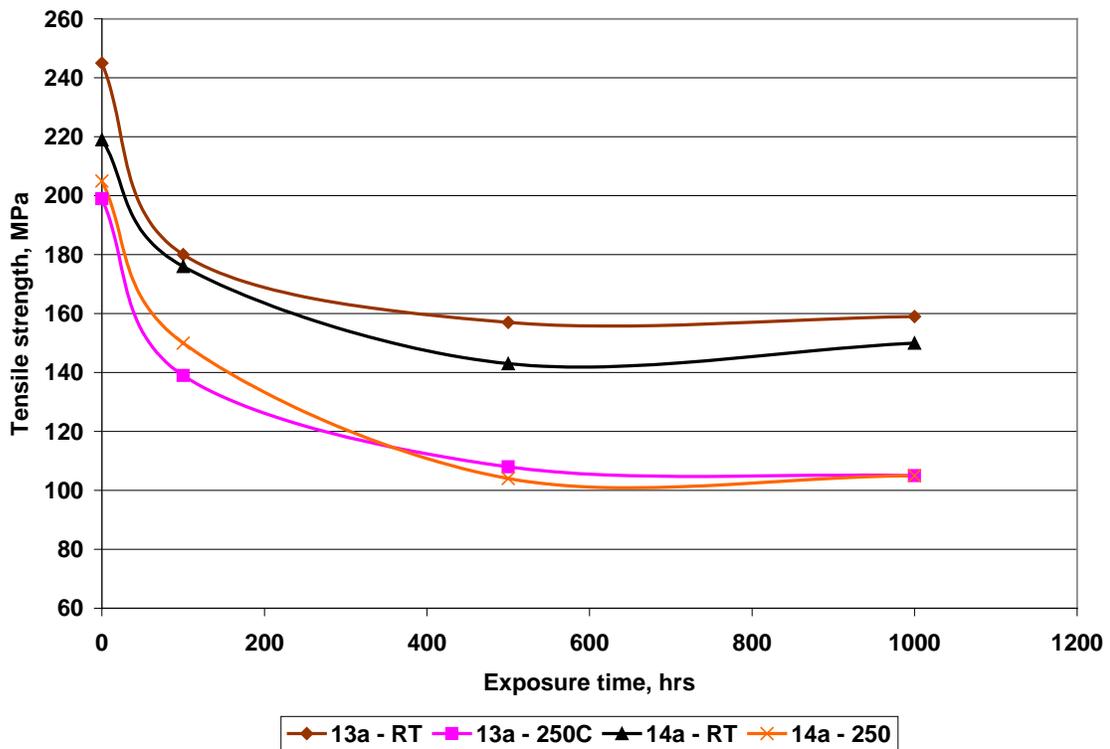


Figure 7: Yield Strength Tensile Properties of Alloys 13a and 14a at Room Temperature and 250°C.

The results indicate the following:

- The room temperature strength of alloy 13 is higher than alloy 14. However no explanation can be provided due to the porosity content of the specimens. Also, alloy 14 contains lower magnesium content and exhibited lower hardness.
- At 250C, the strength of alloy 13 was reduced by 20% while only 5% reduction was observed for alloy 14. However, the values are very similar. This result indicates that the low strength of alloy 14 at room temperature may be solely due to porosity observed in the test sample.
- The strength of the alloys decreases as they are exposed to high temperatures. The drop in properties is nearly 25% after 100 hours. The reduction is less rapid after this time. After 1000 hours the reduction in strength is only 35%.
- The high temperature properties of the alloys suffer more when they are exposed to high temperatures. Nearly 50% of the strength is lost after an exposure time of 500 hrs. After this the reduction is not significant.

The low ductility value prompted the production of another set of tensile test samples using squeeze casting process. Alloy 13 was used for this experiment and subjected to solution treatment at 590°C (comparable to 13a samples discussed above). The tensile test results are presented in Table 9. Even though the room temperature strength of the alloy was lower than the sand cast alloy, the strength after 1000 hr exposure remained higher.

Table 9: Tensile Properties of Squeeze Cast Alloy 13.

Test Temperature	Heat Treated			Exposed at 250°C for 1000 hrs		
	UTS, MPa	YS, MPa	%	UTS, MPa	YS, MPa	%
RT	211.7	175.6	1.4	205.6	158.5	1.9
250°C	143.2	120.5	6.8	117.9	86.8	11.7

3.1.2 Al-Cu-X MMC Alloy Development. This task of the project involved the selection of a ceramic or intermetallic reinforcement that is chemically stable at elevated temperature in an Al-

Cu-X alloy matrix that contains insufficient Si to preclude interaction with carbide based reinforcement particulates and devising a low-cost, liquid-metal mixing technology that can homogeneously incorporate fine (5 to 8 μm diameter) particulates into the aluminum alloy developed in Task 1 of the project. It was also necessary to consider that the resultant MMC alloy system must be capable of being cast into high quality components with cost effective production methods.

Experimental Details

Reinforcement Selection, Characteristics and Treatment. In this work, numerous ceramic or intermetallic particulates that are chemically stable at elevated temperature (250 to 300°C) in an aluminum matrix that does not contain silicon were considered. A listing of the potential oxides, carbides, borides, and nitrides available is given in Tables 10. A similar listing for the potential intermetallic reinforcements is given in Table 11. There are, however, concerns on achieving homogeneous distribution and thermal stability of the intermetallics that are formed in an in-situ fashion in an aluminum matrix.

In view of factors such as thermal stability, ability to attain a homogeneous distribution in the matrix alloy, and cost of the reinforcement powders, it was decided that a low cost alumina powder would be used in this work. Three different particulate sizes of Al_2O_3 powders, namely 17 μm , 10 μm and 7 μm , were considered; as well as Cu coated and Ni coated Al_2O_3 powder. Property information of the powders utilized is listed in Table 12.

Table 10: Candidate Ceramic Particulates for MMC Alloy.

Oxide	Boride	Carbide	Nitride
BeO	TiB ₂	TiC	AlN
MgO	ZrB ₂	ZrC	
ThO ₂		HfC	
ZrO ₂		VC	
CeO		NbC	
Al ₂ O ₃		TaC	
		Mo ₂ C	
		WC	
		B ₄ C	
		SiC	

Table 11a: Candidate Intermetallics for the MMC alloy.

Titanium	Zirconium	Vanadium	Niobium	Tantalum
TiAl ₃	ZrAl ₃	VaAl ₆ VaAl ₁₁	NbAl ₃	TaAl ₃

Table 11b: Candidate Intermetallics considered for the MMC alloy.

Chromium	Molybdenum	Tungsten	Iron	Cobalt	Nickel
CrAl ₇	MoAl ₁₃ MoAl ₁₂	WAl ₅ WAl ₁₁	FeAl ₃ FeCoAl ₄ FeNiAl ₉ FeTi Al ₆ FeMnAl ₆	CoAl ₉ Co ₂ Al ₁₉	NiAl ₃ (NiCu) ₂ Al ₃ NiCoAl ₄ NiFeAl ₉

Table 12: Data for Al₂O₃ Powders used for Development Effort.

Powder	Name	Supplier	Chemical composition	Size		Experimental Run Number
				Vol %	µm	
P1	Al ₂ O ₃ fused Lot 7318	Grains and Powders Saint-Gobain, USA	99.45% Al ₂ O ₃	3	28.8	CA1 and CA17
			0.01% TiO ₂	50	17.4	
			0.02% SiO ₂	94	12	
			0.49% Na ₂ O			
P2	Aluminum Oxide F600 Duralum WP Lot O30705	Washington Mills Electro Minerals Corp., Niagara Falls, NY	96% Al ₂ O ₃	3	18.3	CA2 to CA15 and CA18
			3% TiO ₂	50	10.3	
			1% SiO ₂	94	6.2	
P3	F800 Duralum WP Lot 101005	Washington Mills Electro Minerals Corp., Niagara Falls, NY	96% Al ₂ O ₃	3	13.9	CA20 to CA25
			3% TiO ₂	50	7.4	
			1% SiO ₂	94	3	
P4	F800 Duralum WP Lot 101005, Cu coated	Coatings applied by Advanced Ceramics Lakeview, OH	–	–	5	CA16
P5	F800 Duralum WP		–	–	5	CA19

	Lot 101005, Ni coated					
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Figure 8 shows an SEM micrograph of the as-received Duralum WP 400 alumina powder.

Basically, this has a wide range of the particle size, from 40 m to less

EDXA analyses (Fig. 9) shows that most of the particles are alumina, there are some particles that contain titanium oxide, silicon oxide, calcium oxide and traces of magnesium oxide.

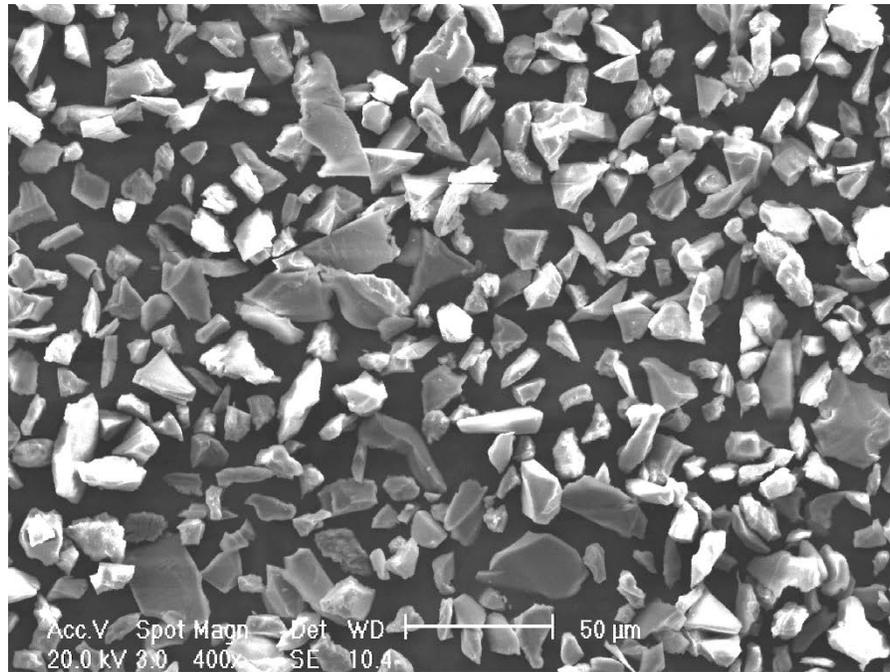
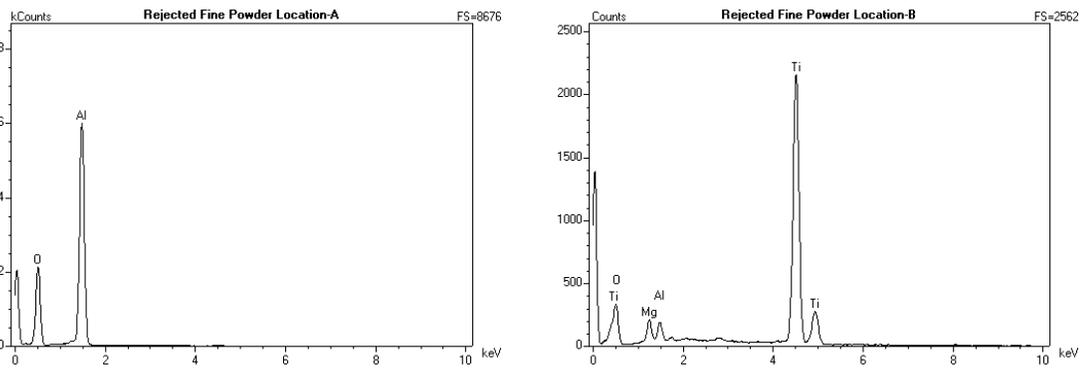


Figure 8: As-received Duralum WP 400 Alumina Powder.



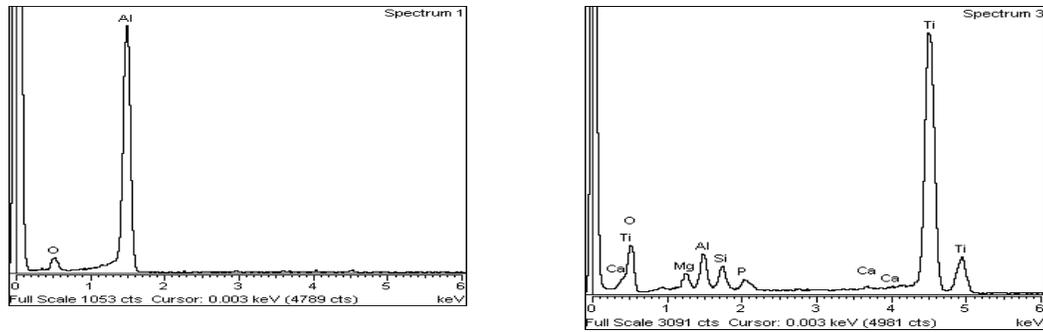


Figure 9: Chemical compositions of various particles found in Duralum WP400 powder.

The Ni coated alumina powder used in this work is shown in Fig. 10. Most of the powders are less than 5 μm in diameter, and they are individual spherical particles. The EDXA spectrums (Fig. 11) taken from different particles (A to E), show that the Ni coating is not uniform. In the case of particle B, the presence of nickel can hardly be detected, though a heavy presence of nickel is identified in other particles (D and E).

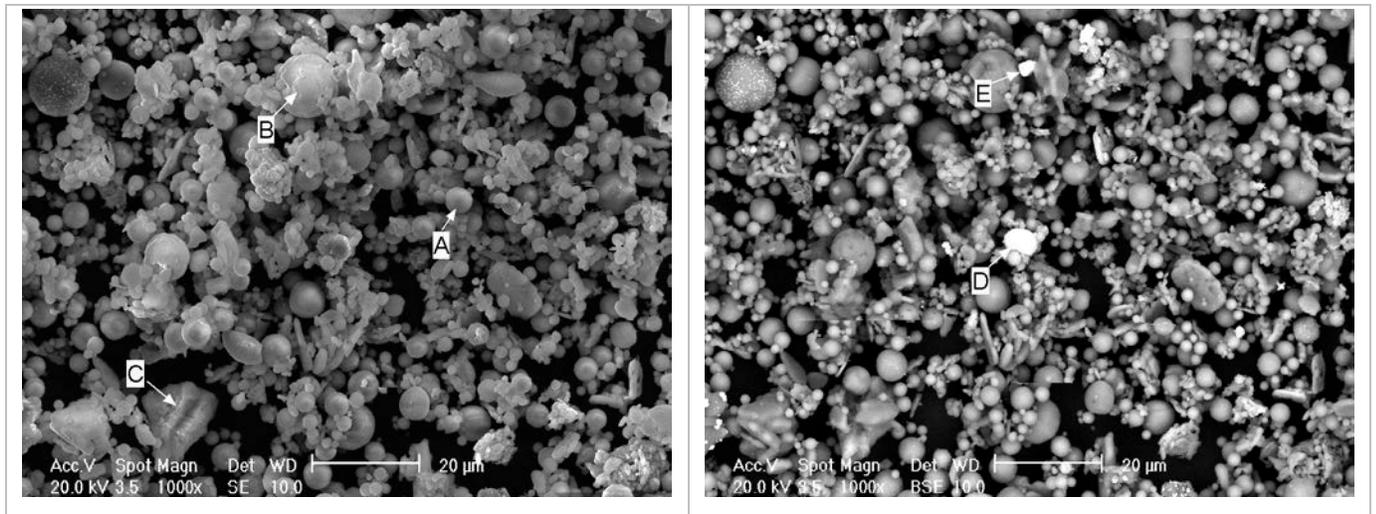


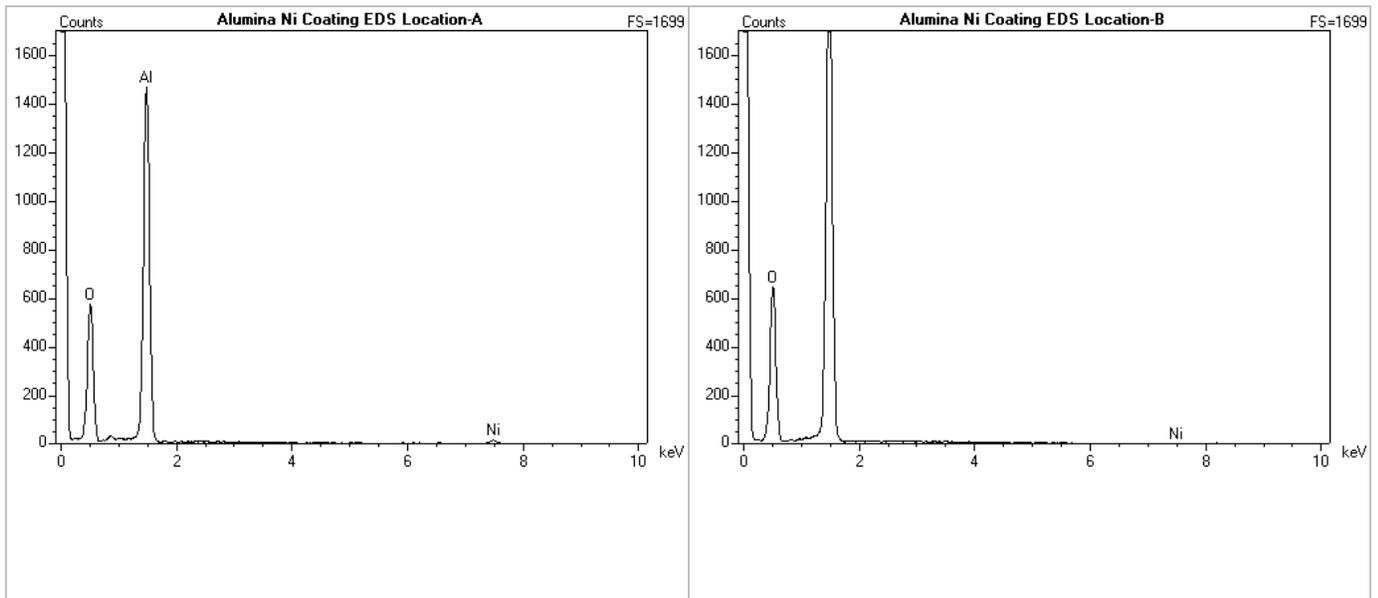
Figure 10: Ni coated alumina powder.

The situation for the Cu coated powder is very similar. Most of these particles are agglomerated (Fig. 12). The particle size range is polarized to the two extremes of over 10 μm and less than 5 μm . The EDXA spectrums (Fig. 13) taken from different particles (A to D), confirmed that the

particles were not uniformly coated. In case of particles A and B, there was no Cu coating at all, though there was a heavy presence of Cu coating on particle C.

Considering that the humidity of the powder would affect the reactivity between the powder and the molten alloy, all powders were pre-treated before addition to the molten Al-alloy(s). Five conditions, as shown in Table 12, were used in this investigation. Only one run (CA24) was conducted with the powder in as received conditions (pre-treatment T5). In all of the runs, the powders were protected under the argon environment during processing.

Matrix Alloy Selection. Prior to the development of a high temperature aluminum alloy in this project, different aluminum alloys were used to determine the process parameters as well as procedures for making stir cast aluminum composites. Preliminary runs were conducted with the standard A206 alloy, to produce aluminum based composites. At the completion of Task 1, the developed Al-Cu-Mg-Sc alloy was used for the later stir casting runs. In total, four types of aluminum alloys were used, and their compositions are listed in Table 13.



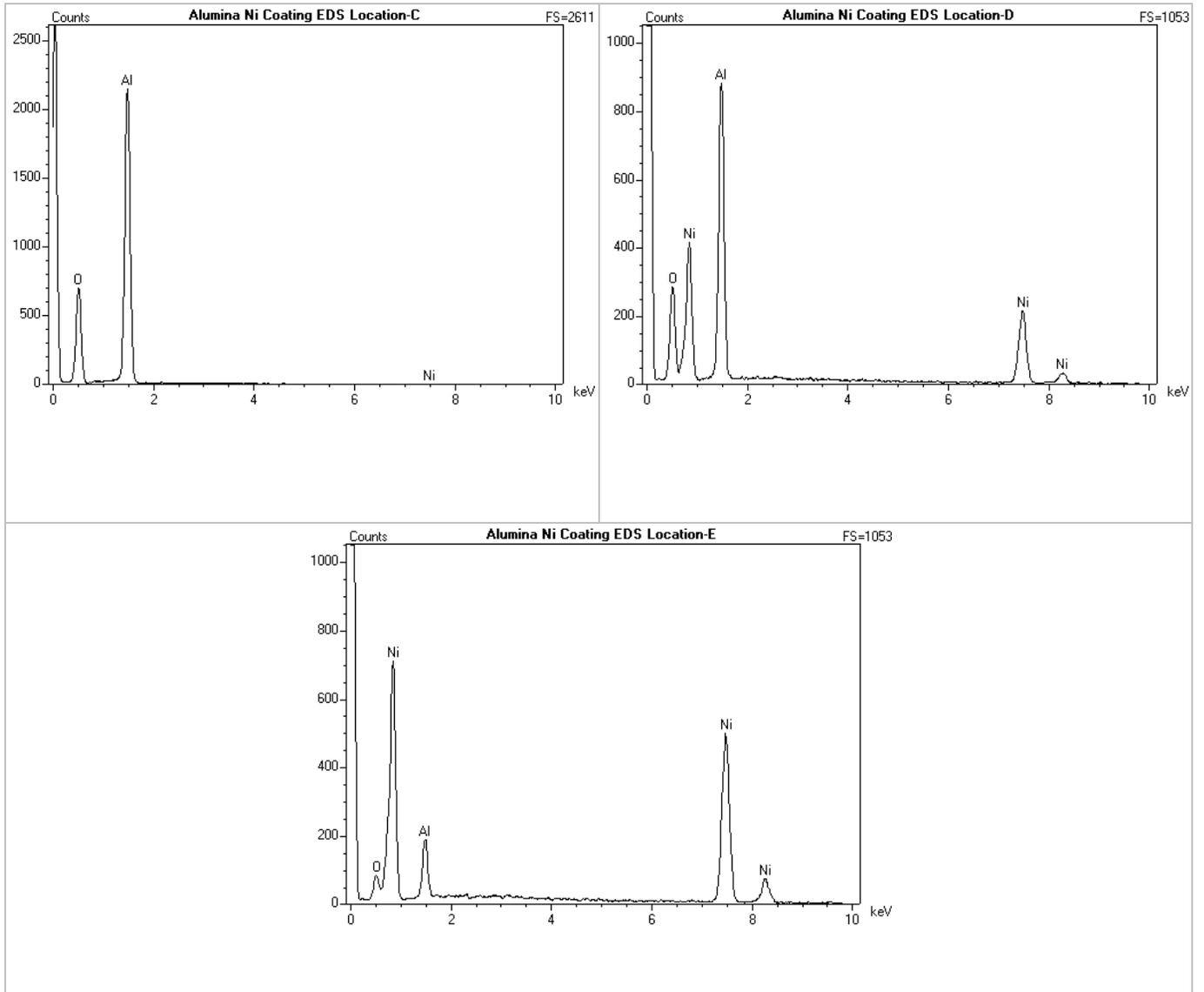


Figure 11: EDXA analyses of Ni coated alumina powder.

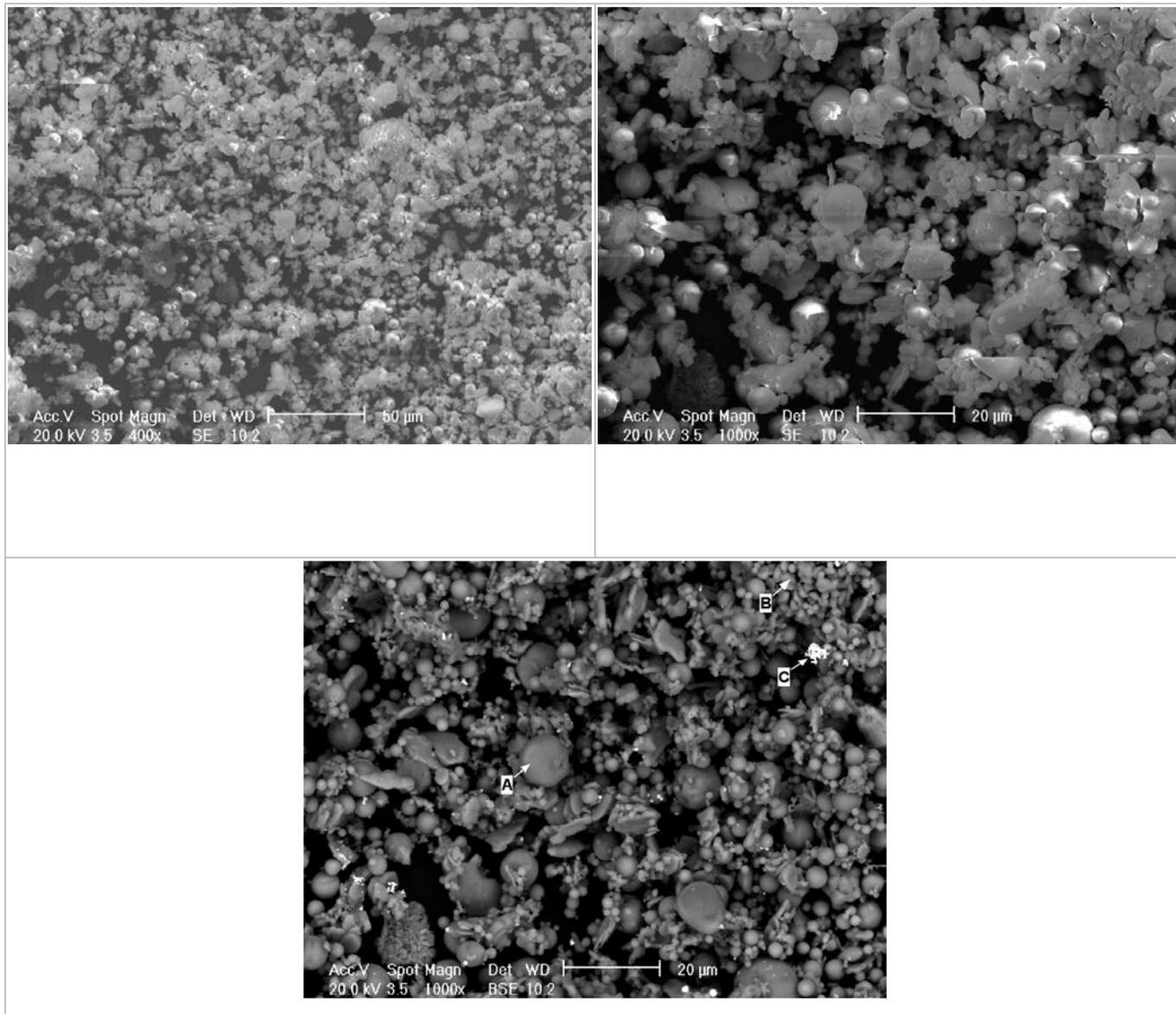


Figure 12: Cu coated alumina powder.

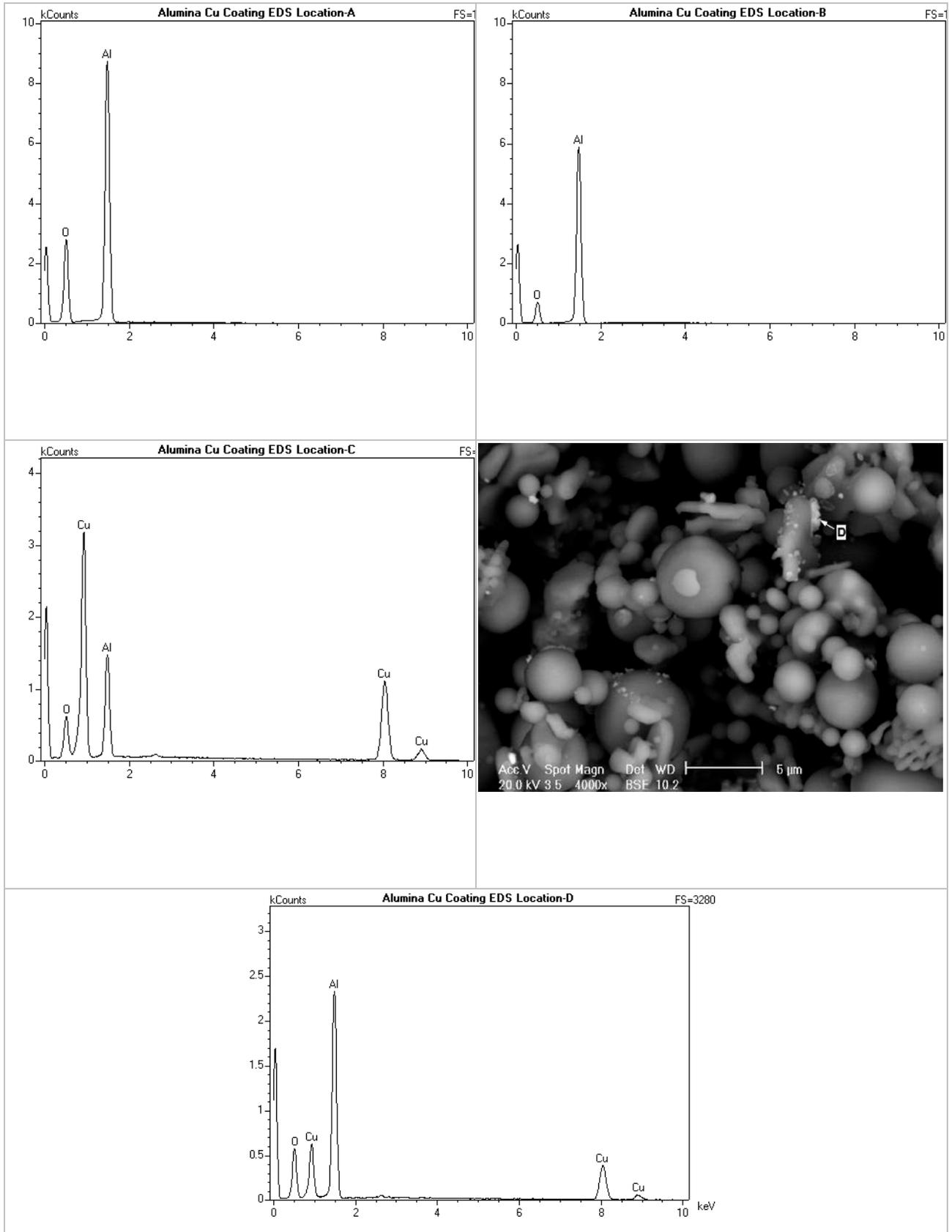


Figure 13: EDXA analyses of Cu coated alumina powder

Table 13: Powder pre-treatment (T) conditions used for stir casting trials.

Treatment notation	Description	Experiment number.
T1	Preheated over night to 200°C, atm. conditions	CA1,CA2, CA8-CA18,CA20-CA23,CA25
T2	Preheated over night to 500°C, in argon	CA3
T3	Flushed with argon at 125°C, then preheated over night to 200°C in argon	CA4 and CA5
T4	Preheated over night to 110°C or to 125°C, atm. conditions	CA6, CA7, CA19
T5	As-received conditions	C24

Table 14: Composition of Al alloys Used for Stir Casting Trials.

	Al	Cu	Mg	Mn	Fe	Ti	Zn	Si	Ni	Sc	Zr
A206	Balance	4.7	0.36	0.2	0.07	0.15	0.05	0.05	0.03		
Alloy X	Balance		0.55					0.12			
Alloy Y	Alloy X modified to attain the composition of Al-Cu-Mg-Sc below										
Al-Cu-Mg-Sc	Balance	2.2	1	0-0.5	0.3	0.03	0	0.5	0.5	0.2	0.03

Experimental Results: Stir Casting Trials

A total of 25 casting runs, identified as CA1 thru CA25, were conducted for this project.

First Casting Series – One Step Process. At the beginning of the project, preliminary runs were conducted with A206 alloy and Al₂O₃ particulates. The reason for such choices was because a

suitable high temperature aluminum alloy was not yet developed, and this alloy was expected to be similar to A206.

For runs CA1 to CA7 (Table 14), composite stir casting was conducted by incorporating the Al₂O₃ powder directly into the molten A206 melt with a One Step process. The first run (CA1) was performed with 17 μm particle diameter Al₂O₃ powder, while the rest of the runs were conducted with 10 μm particle diameter Al₂O₃ powder. Different powder pre-treatment methods, as listed in Table 12, were used for preparing the powder prior to stir casting.

Table 15: List of Stir casting trials used to incorporate Al₂O₃ powders into the AlCu alloys using the one- step process.

Experiment (Heat No.)	Matrix Alloy	Experimental Parameters			Results
		Melt Temp., °C	Stirring parameters		
			Impeller Speed, rpm	Time, min	
CA 1 (N5043)	Al 206 (A1)	690	1500	23	Rejection of powder
CA2 (N5093)	Al 206 (A1)	660-685	1500	54	Rejection of powder
CA3 (N5128)	Al 206 (A1)	700-690	1500	5	Rejection of powder
CA4 (N5148)	Al 206 (A1)	675-680	1500	8	Rejection at the end of feeding. The powder went in after 5 min. of stirring. Tear test samples
CA5 (N5161)	Al 206 (A1)	682-671	1500	12	Rejection at the end of feeding. Prolonged stirring did not help. Extra 0.2% Mg addition after rejection did not help.

CA6 (N5165)	Al-5.5%Zn	685	1500	70	Powder accepted Stirred extra 10 min. after powder incorporated into melt Tear test samples
CA7 (N5168)	Al 206 (A1)	672	600/1000	90	Rejection

The powder stirring rate used was generally at 1500 rpm with the exception of experiment CA7 where the stirring rate was initially 600 rpm and then increased to 1000 rpm. Feed rates for the alumina powder were between 0.5 kg/hr and 9.0 kg/hr.

For trial CA1, the alumina powder was initially accepted into the melt and then rejected when about 9 volume % of reinforcement had been added to the melt. Chemical analysis determined that the matrix alloy, after stir casting, contained less Mg and more Si and Fe. The lower Mg content was not a surprise because alumina will often react with Mg in the melt to form a spinel or MgO on the surface of the alumina powder. Commercial alumina powders generally contain some SiO₂ and FeO and this may be the source of the elevated Si and Fe contents in the matrix. Inadequate coating of the iron containing stirring tool may also have been a source for the higher iron content.

Since the powder was rejected from the melt repeatedly (experiments CA1 to CA5) after initial incorporation, a run was conducted to verify the suitability of the alumina powder by switching to an Al 5.5% Zn alloy (Experiment CA6). Prior research had shown that the stir casting process could successfully incorporate alumina particulates into an

Al 5.5% Zn matrix. The powder was readily incorporated into the Al 5.5% Zn alloy thus, verifying the suitability of the powder for the stir casting process. Following this run, one more run was conducted with an A206 melt using the same procedure as used for trial CA6. Unfortunately, the powder was again rejected.

Comparing experimental runs CA1 and CA2, both the powder and the alloy used were supplied by Eck Industries. In CA2, the average particle size for the reinforcement is 10 m instead

as in the CA1 run. The intended volume fraction of reinforcement is lowered in this case. Similar to the previous run, the powder was readily accepted into the melt at the beginning of the stir casting run. Almost 2 vol % of reinforcement was incorporated into the melt, before the rejection of powder was noticed. The average reinforcement particle size is smaller compared to previous run (10

□m instead

higher. It is possible more air was trapped in the finer powder clusters, and more wetting was required. Both the rejected powder and the matrix alloy were also examined using scanning electron microscope (SEM) and chemical analysis respectively. The chemical analysis results indicated changes in alloy composition similar to those in the previous run. That is, the silicon content increased from 0.02% to 0.054%; the iron content from 0.058% to 0.70%, and magnesium content decreased from 0.34-0.28%.

Substantial effort was made to understand why the alumina powder often was rejected from the A206 alloy. Initially, the as-received (A) and rejected powder (R) batches were examined using scanning electron microscopy. Despite the color difference (different shades of grey) between A and R powder types, the EDX analysis did not reveal a distinct difference between the two. Further examinations with transmission electron microscopy and X-ray analysis also indicated the presence of alumina spinel, titanium oxide and CuAl_2 in both powder types, and rejection of powder due to the change of chemical composition of the powder surfaces was not confirmed.

Second Casting Series – Two-Step Process. Based on the unsuccessful results obtained in the first series of runs, a second series of runs was conducted using a Two Step process. The process modification was designed to provide better control in getting particles wetted by aluminum prior to adjusting the chemical compositions of the matrix alloy. The first step of the process incorporates alumina particulates into an Al-Mg-Si alloy matrix known to wet alumina particulates. The second step adds a molten alloy with a chemical composition that combined with the molten Al-Mg-Si/ Al_2O_3 composite produces the desired Al-Cu-Mg-Sc matrix alloy composition.

The casting runs for this series are identified as CA8 to CA15 and the process parameters are listed in Table 15. The two step technique allowed the powder incorporation in Al-Cu-Mg-Sc alloy to produce composites with 5 and 10% Al_2O_3 (experiments CA8 and CA9, respectively). The typical

process parameters were: 680°C alloy temperature, 1600 rpm stirring speed, 3 kg/hr and/or 4 kg/hr powder feed rates and 10-12 min. stirring time for homogenization after the Y step.

Since macro-examination on the cast ingot (Trials CA8 & CA9) showed some large agglomerations of particulates and porosity present in the cast composites, further trials were conducted with longer stirring times after each of the X and Y steps. The macro-examination of the samples taken from the ingots indicated that, even with additional stirring of 30 min. after each X and Y steps (run CA11), Al₂O₃ particulates were still found in clusters. And when the stirring time was further increased up to 70 min. (runs CA10, CA13, CA14), the powder was rejected despite an increase in Mg content (from 0.55-0.85%) in step X. In conclusion, neither longer stirring time nor faster stirring speed improved the particulate distribution nor decreased the amount of porosity. In fact, it is very likely that longer stirring time and faster stirring speeds introduced more air into the melt, causing the particulates to be de-wetted.

Third Casting Series – Developed Al-Cu-Mg-Sc Alloy. Experimental runs CA16 to CA25 (Table 16) were conducted with the developed Al-Cu-Mg-Sc alloy as matrix alloy to produce Al₂O₃ reinforced composites. The CA16, CA19 and CA24 runs were conducted using the One Step process. The first two runs used Al₂O₃ coated with Cu and Ni, while the as-received P3 powder was used in the CA24 run. With the exception of Al₂O₃ coated with Ni (CA19), all powders used were rejected when the One Step stir process was used with the Al-Cu-Mg-Sc alloy. Subsequently, all other experiments were performed using the Two Step process.

Both the as-received copper and nickel coated alumina powders have a higher tendency to cluster as compared to the uncoated alumina powder. It is known that clusters of particles contain trapped air, and their incorporation into a molten melt could lead to gas bubble formation. As a result, the use of the as received copper and nickel coated alumina powders for stir cast alumina/aluminum (Al-Cu-Mg-Sc alloy) composites did not yield good castings. In fact, the use of uncoated Duralum alumina powder in stir casting alumina/aluminum composite provided better cast ingots. This finding confirms that the extensive clustering found in the as-received Cu and Ni coated Al₂O₃ powder is maintained during the stir casting process as compared to the uncoated Al₂O₃ powder.

The uncoated Al₂O₃ powder was used for runs CA17, CA18, CA20, CA21 and CA25. Due to the fact that the magnesium content in the Al-Cu-Mg-Sc is higher than in A206 alloy (1% Mg by comparison with 0.35%, Table 1), it was possible to use an alloy X composition containing an increased Mg content (up to 2.3%).

Although the higher feed rate (8-6 kg/hr) used for trial CA17 incorporated the alumina powder into the melt its use is not recommended since loose powder was found at the bottom of the crucible after a run. Consequent, remaining trials were performed with lower feeding rate (3-4 kg/h). Feeding was performed starting with a minimum 600-700 rpm, and with the increase of the liquid viscosity due to the powder addition, it was gradually increased to 1250 rpm. The alloy temperature during the powder addition varied between 667and 687°C.

Table 16: List of Stir casting trials used to incorporate Al₂O₃ powders into Al-Cu alloys using the two-step process.

Casting run	Steps in the process	Stirring Parameters			Results
		Melt Temp., °C	Speed, rpm	Time, min.	
CA 8 (N5169)	Step 1: Alloy X (Al-0.55%Mg-0.12%Si)	680	1600	42	Powder accepted – Pour tear test bars (375/680°C)
		680	1600	12	
	Step 2; Alloy Y (Al/Mn/Cu/Ni)	680	1600	10	
CA9 (N5173)	Step 1: Alloy X (Al-0.55%Mg-0.12%Si)	680	1600	65	Powder accepted – Pour tear test bars (370/682°C; 340/680°C and 331/681°C)
				10	
	Step 2 : Alloy Y (Al/Mn/Cu/Ni)	680	1600	15	
CA10 (N5182)	Step 1: Alloy X (Al-0.53%	680	950	55	Powder rejection – Rejection after 55 min. (X). Stop powder

(repeat CA9)	Mg-0.12%Si)				addition. Continued stirring and the powder went in. – Rejection after 60 min. of stirring. Stop processing.
			1600	60	
CA11 (N5183)	Step 1: Alloy X (Al-0.85% Mg-0.12% Si)	680	950	75	Powder accepted
		680	1600	30	
	Step 2 : Alloy Y (Al/Mn/Cu/Ni)	680	1600	30	
CA12 (N5085)	Remelt ingots CA11	662-680	1600	17	Rejection after 17 min. of stirring
CA13 (N5233)	Step 1 Alloy X (Al-0.7% Mg- 0.14% Si)	677-680	950/1600	72	Rejection after 40 min. extra stirring after the powder addition (X).
		680	2000	40	
CA14 (N5246)	Step 1 Alloy X (Al-0.7% Mg- 0.13% Si)	680	950	70	– Rejection at the end of powder addition (X)
CA15 (N5267)	Step 1 Alloy X (Al-0.7% Mg)	680	1600	30	Rejection after 70 min. stirring with Y
			2000	30	
	Step 2 : Alloy Y (Al/Mn/Cu/Ni)	666-681	1600	70	

Table 17: List of Stir casting trials to incorporate Al₂O₃ powder into Al-Cu-Mg-Sc alloys using one-step process.

Casting Run Number	Process	Comments			
		Melt Temp. °C	Stirring Parameters		Results
			Speed, rpm	Time, min.	
CA 16 (N6007)	One Step process: powder added to the final composition	677-680	1600	12	
CA17 (N6009) Target 10% Al ₂ O ₃	Step 1: Alloy X (Al-2.0%Mg)	668-685	1600	45	Powder accepted. – Rejection after 30 min. (X). Stop powder addition and continued stirring. Powder went back in the Al-Mg alloy. Experiment continued.
		680	2300		
	Step 2 : Alloy Y (Al/Mn/Cu/Ni/Sc)	665-686	2300	105	
CA18 (N6019) Target 10% Al ₂ O ₃	Step 1: Alloy X (Al-1.9%Mg)	682-685	1100/1600	60	Powder accepted – Slices from ingots used for squeeze casting.
		680	2300	30	
	Step 2 : Alloy Y (Al/Mn/Cu/Ni/Sc) Added extra 1.25% Mg	680	1600	105	
CA19 (N6017)	One Step process: powder added to the final composition	678-685	1600	30	– Powder accepted
				30	– Ingots only
CA20 (N6018) Target 10% Al ₂ O ₃	Step 1: Alloy X (Al-2.3% Mg)	668-685	600/950/1250	15	Powder accepted. – Rejection after 15 min. Stop addition. Continued addition with increased speed rate. – Slices from ingots used for squeeze casting.
				40	
	Step 2 : Alloy Y (Al/Mn/Cu/Ni/Sc)	663-677	600	10	

CA21 (N6052) Target 7% Al ₂ O ₃	Step 1 Alloy X (Al-2.3% Mg)	665	750/950/1 250	53	Powder accepted – Trimming for the final composition of the matrix was done by adding solid pieces of master alloys in X after the powder addition. – Cast ingots using filters. – Used for squeeze casting trials. – Used for remelting in vacuum.
				40	
	Step 2 : pieces of master alloys added to P3/X composite		-	152	
		667-688	1250	60	

Table 17 – (cont'd)

Heat No.	Process	Comments			
		Melt Temp., °C	Stirring Parameters		Results
			speed, rpm	Time, min.	
CA24 (N6068) Target 7% Al ₂ O ₃	One Step process: powder added to the final composition	667-644 660	700 950		
CA25 (N6073) Target 7% Al ₂ O ₃	Step 1: Alloy X (Al-2.2% Mg) Step 2 : Alloy Y (Al/Mn/Cu/Ni/Sc)	668-685 680 680	700 1250 1250	15 40 10 10	Powder accepted – Rejection after 15 min. Continued stirring 10 min. without feeding. Add powder again. Continued the process. – After 10 min. of stirring the final alloy composite were poured 4 ingots. The remaining composite was stirred 20 min. longer before pouring ingots. – Slices from ingots used for squeeze casting.

Castings were performed with stirring times ranging from 10 min. (CA21) to 105 min. (CA18) with no detectable improvement of the particle distribution was noted with the extended stirring time after the Y step. In fact, similar conclusion can be drawn that there is no benefit in extended stirring time.

The re-melting and re-casting of sample (CA21) in air environment did not show any significant improvement in porosity reduction or uniform particle distribution. When the re-melting and re-casting of sample (CA21) was done in vacuum environment, the porosity in the sample was drastically reduced. Figure 14 shows the cross-section of the ingot which was re-melted and re-cast in vacuum environment. Though the porosity is reduced, the particles in the composite are found segregated at the top section of the ingot. This is possibly due to the fact that particles originally adhered to the pores were brought to the top of the ingot by the bubbles during vacuum melting process.

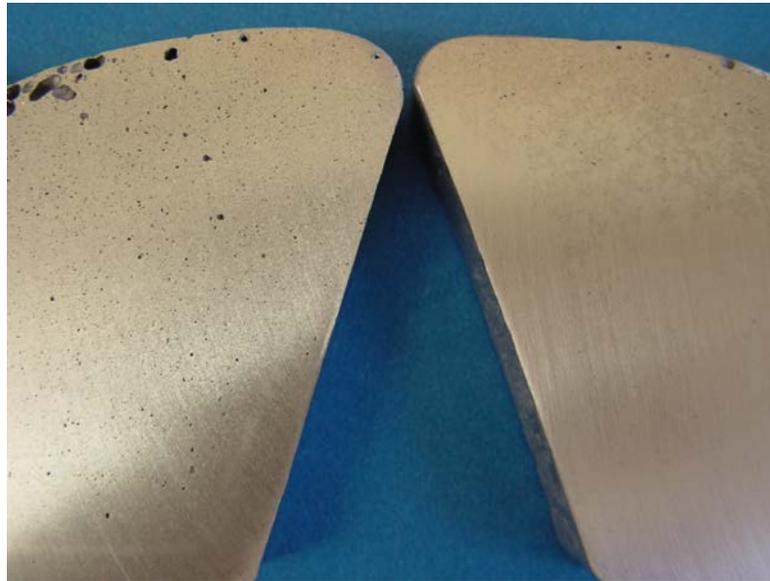


Figure 14: Effect of vacuum re-melt and re-casting on porosity and particle segregation of F800 alumina/AlCuMgSc alloy. Note that the vacuum cast (right) ingot contains less porosity and particle segregation than the stir cast (left) ingot.

In view of the segregation caused by the vacuum re-melt and re-cast process, it is decided that such a step would not provide an added advantage for making F800 alumina/Al-Cu-Mg-Sc alloy composite. However, the result of this experiment does clearly demonstrate the benefit of stir casting under vacuum. If the whole stir casting operation was to be conducted in vacuum, and one has the stirring device incorporated in the vacuum furnace, a sound composite with uniform particle distribution should could be obtained.

Composites with 10% Al_2O_3 (CA20) and 7% Al_2O_3 (CA21 and CA25) in Al-Cu-Mg-Sc alloy were produced with the Two Step process. The composites were cast by gravity in permanent moulds with the dimensions 9 cm by 28 cm by 6 cm.

When the F800 alumina was used, the stir cast sample shows a lesser amount of porosity compared to the stir cast sample made with the F600 alumina powder (Figs. 15 and 16). Figures 17 and 18 show the squeeze cast and as stir cast samples made with F800 alumina powder and Al-Cu-Mg-Sc alloy. It is evident that the stir cast sample contains many visible pores, and such pores were eliminated after the squeeze casting operation. And no porosity was observed even when the sample was examined with an optical microscope at 500X.

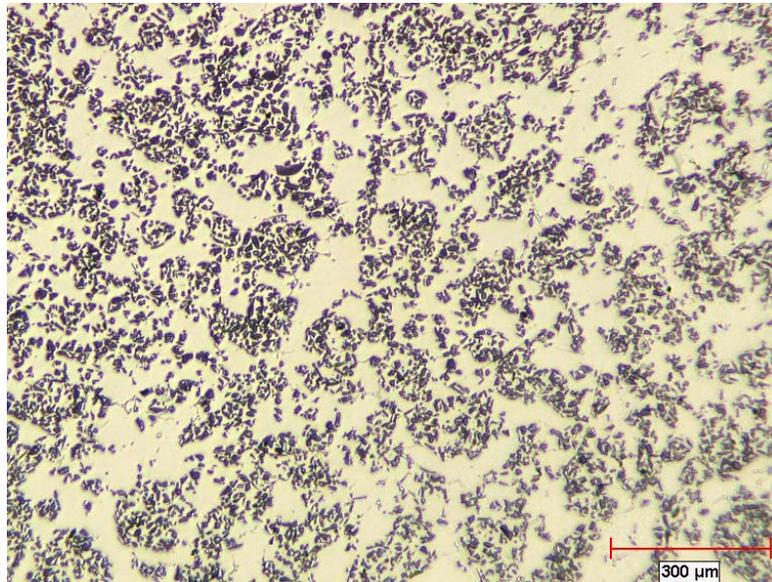


Figure 15: Microstructure of squeeze cast F600 alumina/AlCuMgSc alloy.

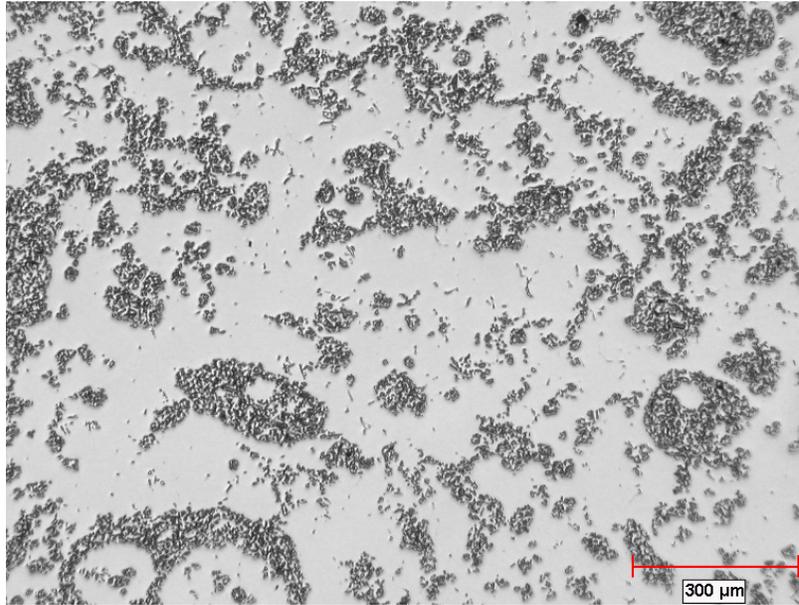


Figure 16: Microstructure of squeeze cast F800 alumina/AlCuMgSc alloy.

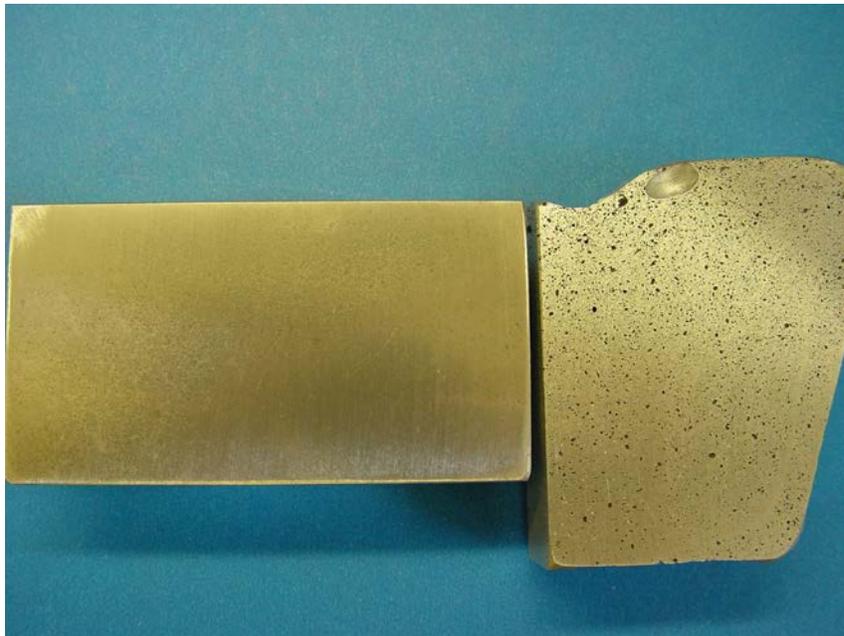


Figure 17: Macrostructure of squeeze cast (left) and stir cast (right) F600 alumina/AlCuMgSc MMC.

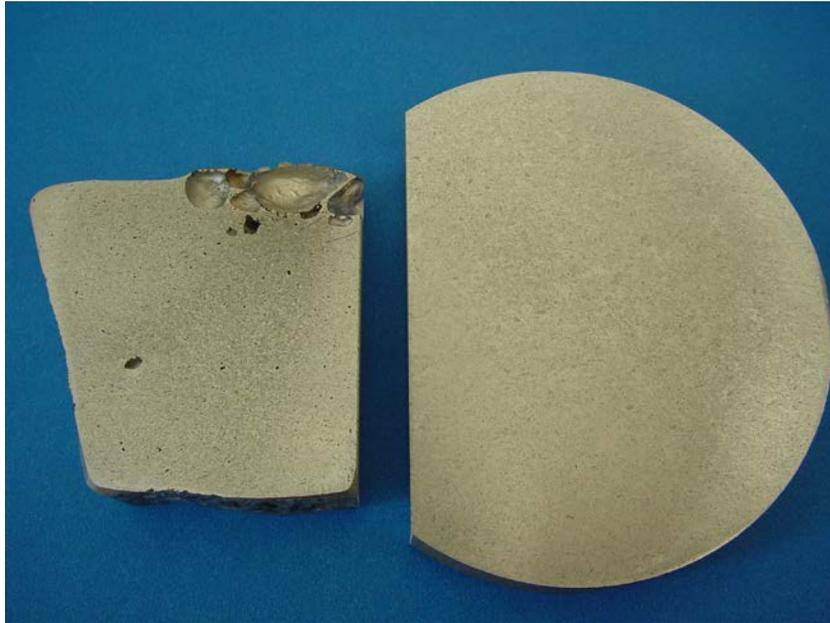


Figure 18: Macrostructure of Stir cast (left) and squeeze cast (right) F800 alumina/Al-Cu-Mg-Sc MMC.

Characterization of Cast Composites

Detailed TEM work (CA15) was conducted to understand the interfacial characteristics between the Al_2O_3 particles and the aluminum matrix. The square grid in Fig. 19 shows the compositional data points being taken across the particle/matrix interface, while Fig. 20 shows the compositional profile on the particle periphery. It is clear that the high levels of magnesium and silicon were detected at the interface. This phenomenon was found in all composite samples examined in this work, as illustrated in the case shown in Fig.21.

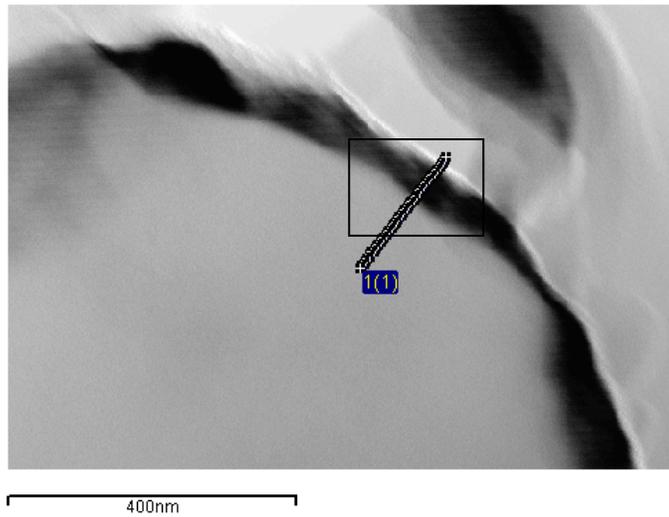


Figure 19: Location of compositional data points across the alumina particle/matrix interface.

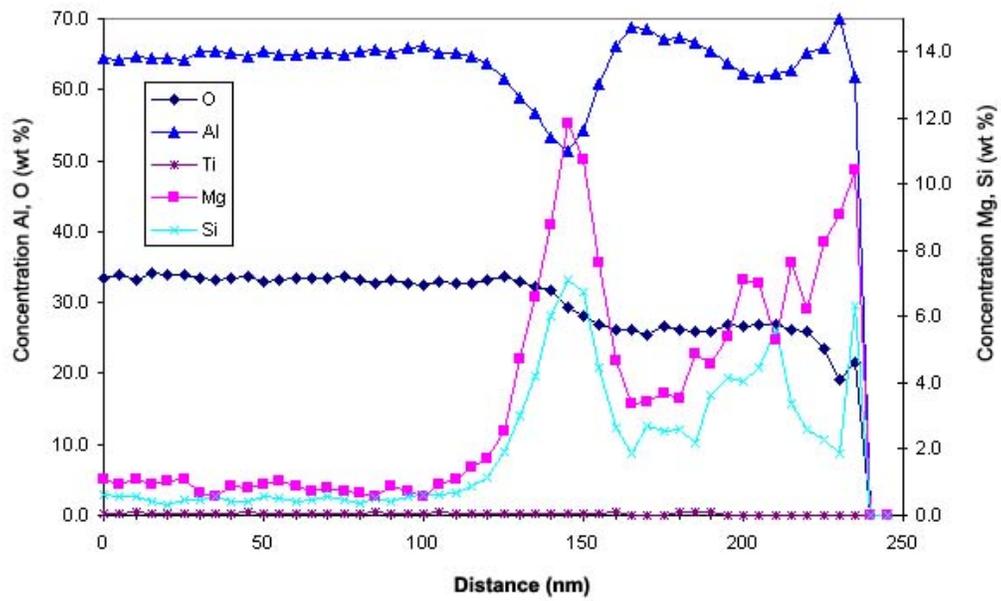


Figure 20: Compositional profile on alumina particle periphery.

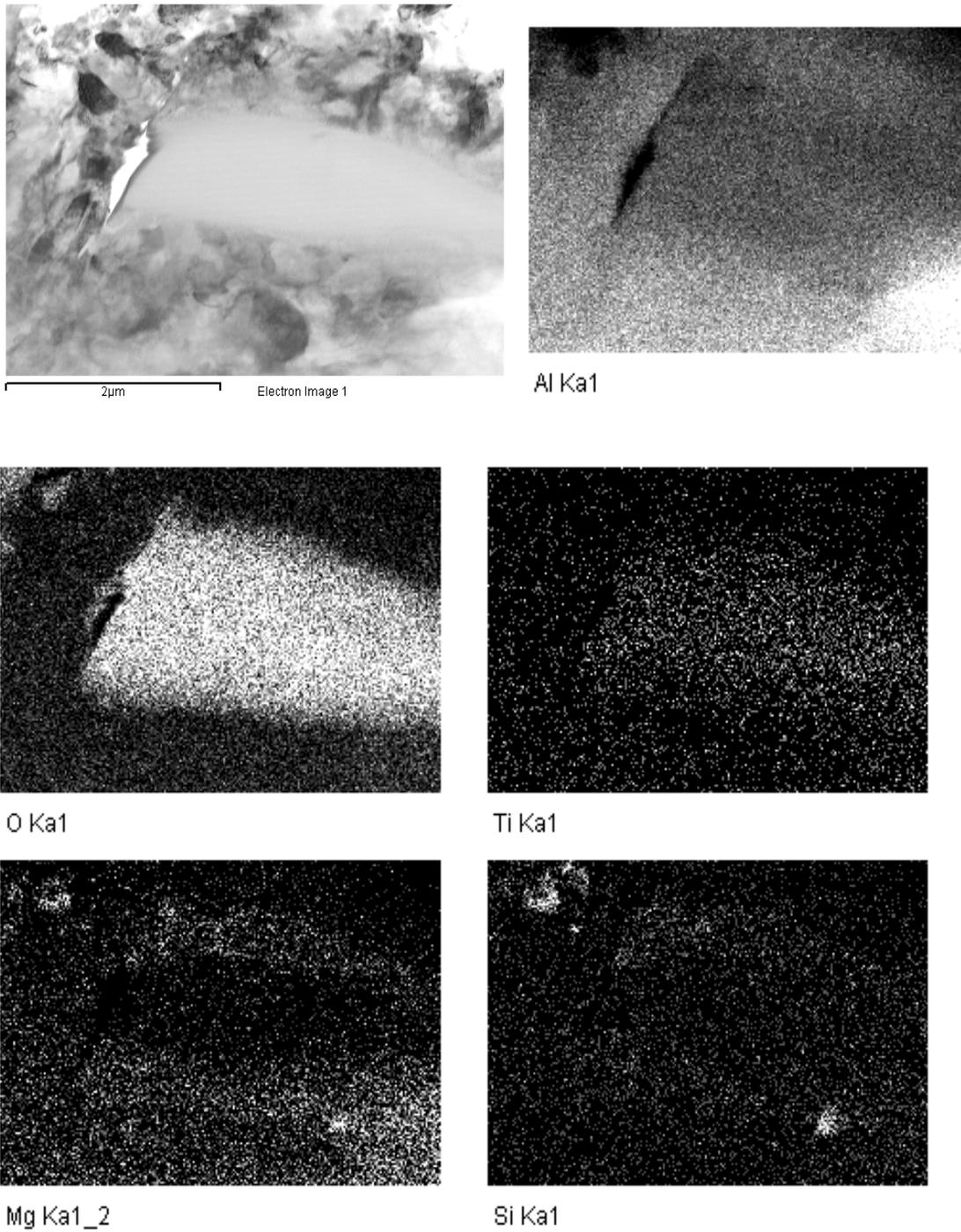


Figure 21: EDAX maps of various elements found at interface between alumina particle and the AlCuMgSc matrix alloy.

Mechanical Properties

Tables 18 and 19 list the mechanical properties of both the matrix alloy and the composite at both room and elevated temperature conditions. It is of interest to compare the measured strength with theoretical predictions for particle strengthening. Using the first approximation of the “shear-lag” model [17, 18], which assumes that the particles are uniformly distributed, the particles are loaded by shear forces at the interface, and the tensile stresses at the particle ends are unimportant. On the basis of this model, the modulus of the composite obeys the rule of mixtures as follows:

$$E_c = V_p E_p + V_m E_m$$

Where E_c is the modulus of the composite, and E_p and E_m are the moduli of particle and matrix; V_p and V_m are the volume fractions of particle and matrix, respectively.

Table 18: Tensile properties of alloys 13 and 14.

Alloy		Heat treated		100 hr exposure		500 hr exposure		1000 hr exposure	
		RT	250°C	RT	250°C	RT	250°C	RT	250°C
13 – sand cast	UTS	245	199	180	139	157	108	159	105
13 – squeeze cast	UTS	212	143					206	118
14 – sand cast	UTS	219	205	176	150	143	104	150	105

Table 19 -Tensile properties of squeeze cast alloy 13.

Condition	Test temperature	Heat treated			Exposed at 250°C for 1000 h		
		UTS	YS	%	UTS	YS	%
Base alloy	RT	211.7	175.6	1.4	205.6	158.5	1.9
	250°C	143.2	120.5	6.8	117.9	86.8	11.7
MMC	RT	227.5	198.3	0.7	192.8	166.6	0.8
	250°C	162.4	142.8	3.8	127.8	102.7	4.9

For this work, a value of $E_p = 300$ GPa has been used for Al_2O_3 powder, and $E_m = 70$ GPa for an aluminum alloy. For an aluminum alloy containing 10 volume % of Al_2O_3 particles this gives us the estimated composite modulus of

$$E_c = 93 \text{ GPa}$$

The shear-lag analysis gives the composite strength as

$$\sigma_c = (V_p \sigma_p S/4) + V_m \sigma_m$$

where σ_m is the matrix yield strength, and S the aspect ratio

Using the above approximation, the estimated strength of the composite is $\sigma_c = 184.38$ MPa, comparing to the matrix yield strength of $\sigma_m = 175.6$ MPa. The estimated yield strength is a bit lower than the measured strength of 198.3 MPa. This is understandable, since other factors which lead to the strengthening of composites such as (i) increased density of dislocation due to thermal mismatch between aluminum and Al_2O_3 particles, (ii) heat treatment, and (iii) subgrain boundaries, have not been considered.

The microstructures of the squeeze cast composite samples (S813-S816) which were $Al_2O_3/Al-Cu-Mg-Sc$ composite from casting run (CA25) are shown in Figs. 22 (5.1), 23 (5.4) and 24 (5.6). After subjecting to heat treatment, various test samples were tested at both room temperature and at 250°C. SEM micrographs Figs. (5.2), 5.3, 5.5 and 5.7

reveal the fracture surfaces of the tensile tested samples conducted at different temperatures. Generally, the Al_2O_3 particles are quite well distributed in the matrix alloy, though clustering of particles was occasionally found. From the tensile test data, it is clear that the extended heat treatment (1000 h) did not provide added benefit to either the strength or the ductility of the composite. The fracture surfaces in both cases (Figs. 5.2 and 5.3) demonstrated brittle failure. When the composite samples were tested at 250°C, the one with extended heat treatment showed a more quasi-cleavage failure due to its lower strength and higher ductility.

Conclusions

1. Al_2O_3 particulate are a suitable reinforcement for improving the high temperature property of the Al-Cu-Mg-Sc alloy from both a cost and fabrication standpoint.
2. Both copper and nickel coated Al_2O_3 powders are unsuitable reinforcements due to clustering of the particulates (in as-received condition) and costs. The formation of particulate clusters occurred during the coating process.
3. A heavy presence of Mg and Si is often found at the interface between Al_2O_3 particles and the matrix aluminum alloy containing magnesium.
4. Fabrication of an Al_2O_3 / Al-Cu-Mg-Sc metal matrix composite (MMC) by the stir casting would probably be best accomplished in a vacuum atmosphere.
5. A 2 step (X + Y) stir casting process has been developed for the fabrication of Al_2O_3 /Al composite using the developed Al-Cu-Mg-Sc elevated temperature capable alloy.
6. An improvement in modulus, tensile strength and yield strength of Al-Cu-Mg-Sc alloy was achieved by the addition of Al_2O_3 powder to form an Al_2O_3 /Al-Cu-Mg-Sc composite.

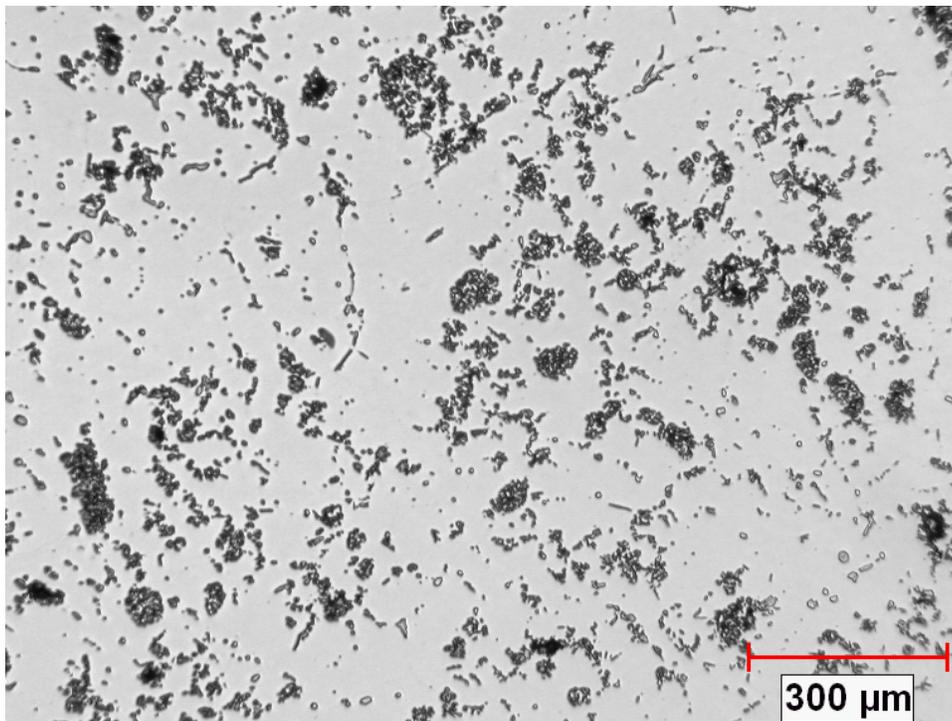
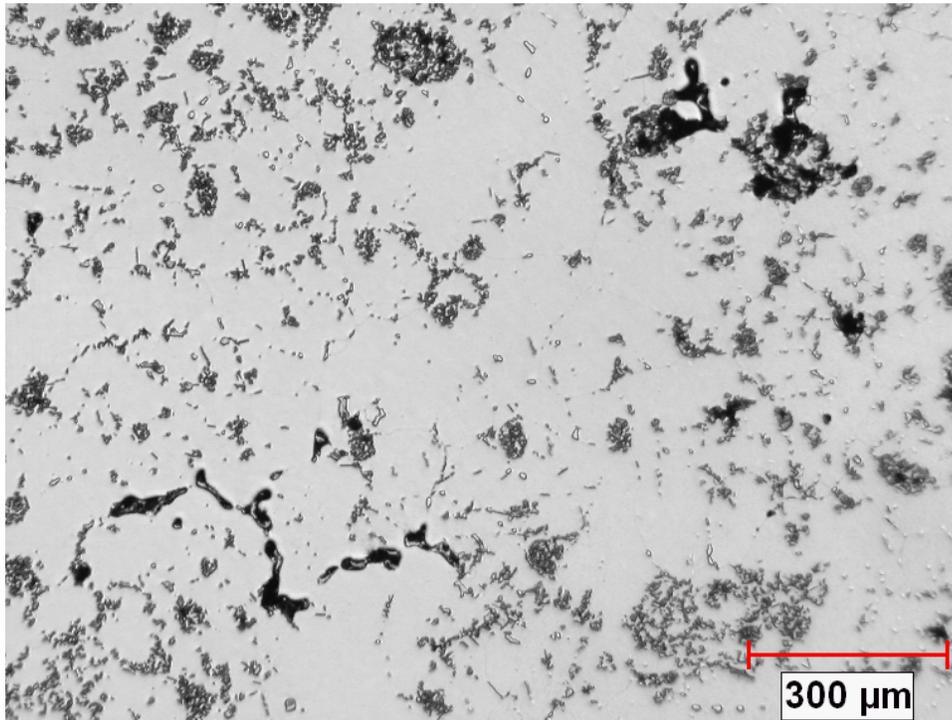


Figure 22: Microstructure of squeeze cast Al₂O₃/AlCuMgSc composite (CA25).

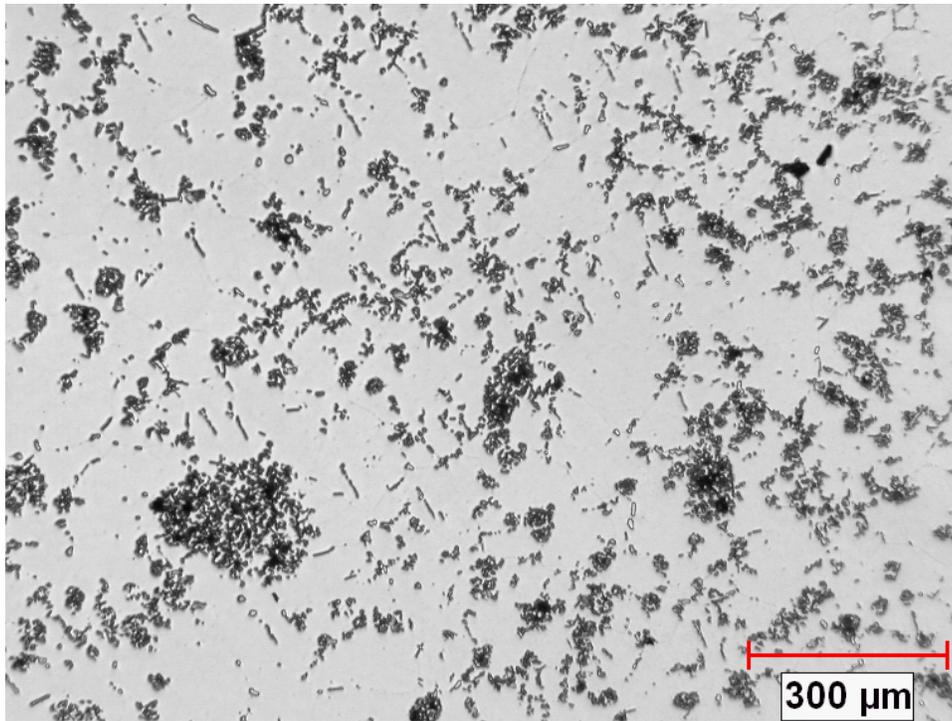
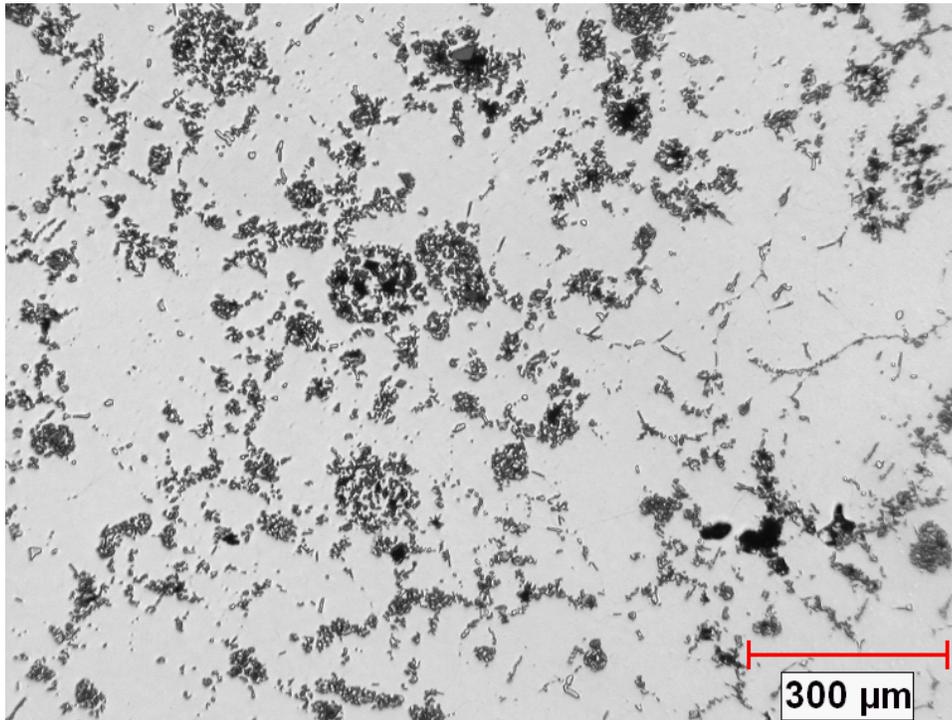


Figure 23: Fracture surface of AlCuMgSc/alumina MMC (S812) after exposure at 250°C for 1000 hours. Tensile test accomplished at room temperature.

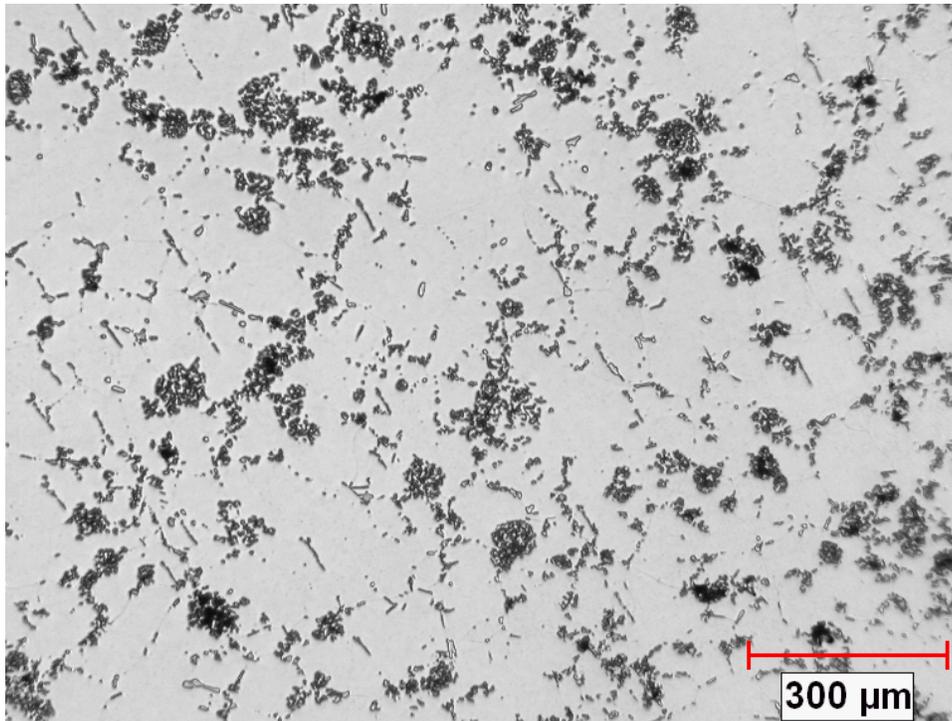
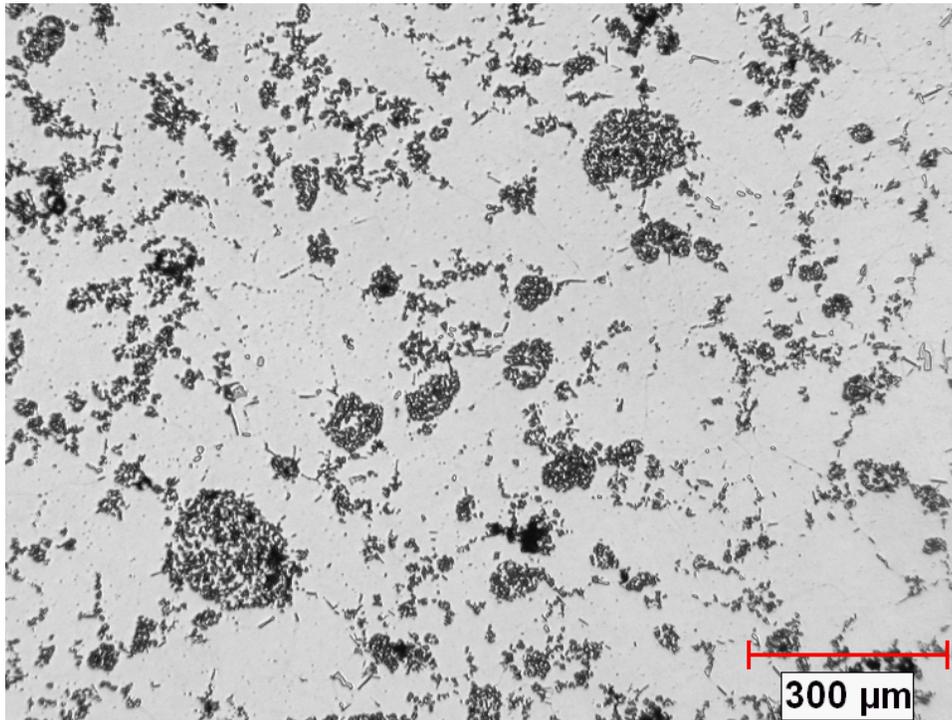


Figure 24: Fracture surface of AlCuMgSc MMC (S812) after exposure at (250°C for 1000 hours. Tensile test accomplished at 250oC.

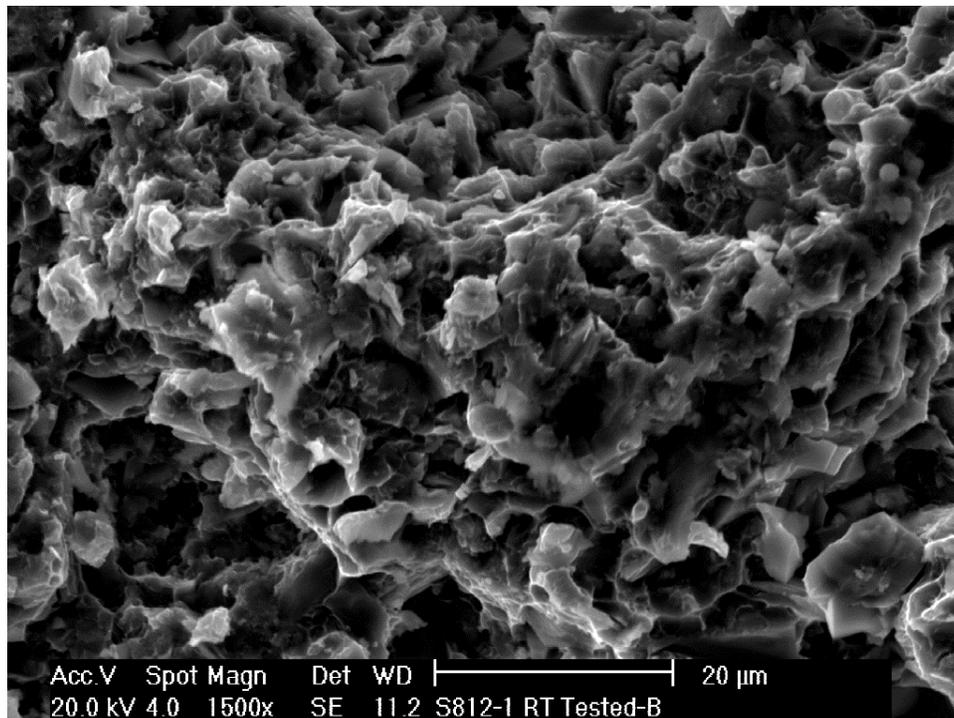
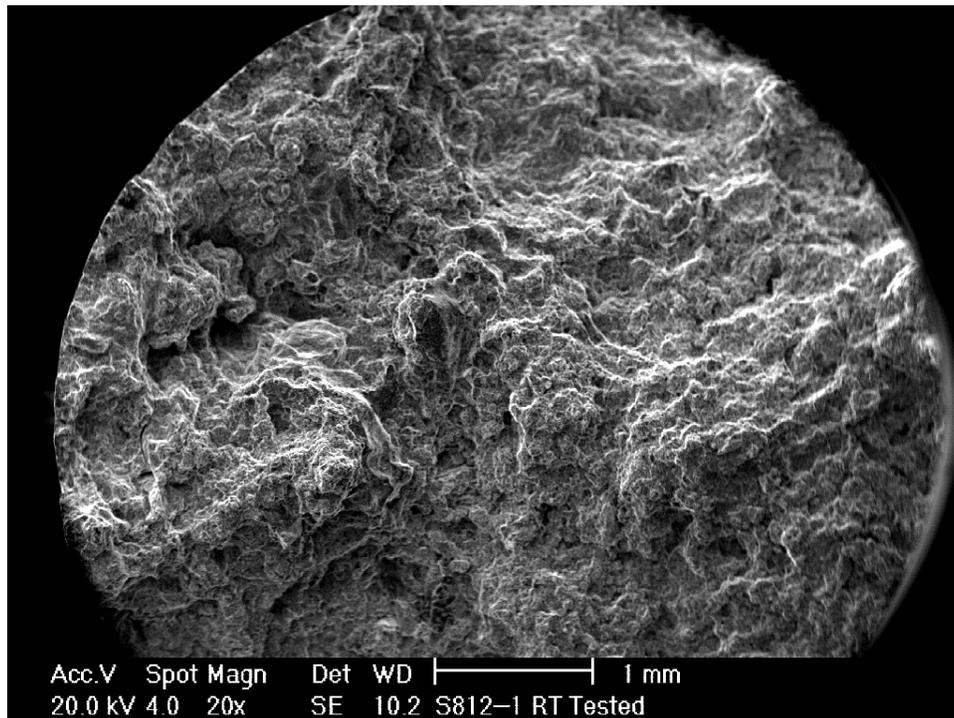


Figure 25: Fracture surface of S812 tensile tested at room temperature; showing brittle failure.

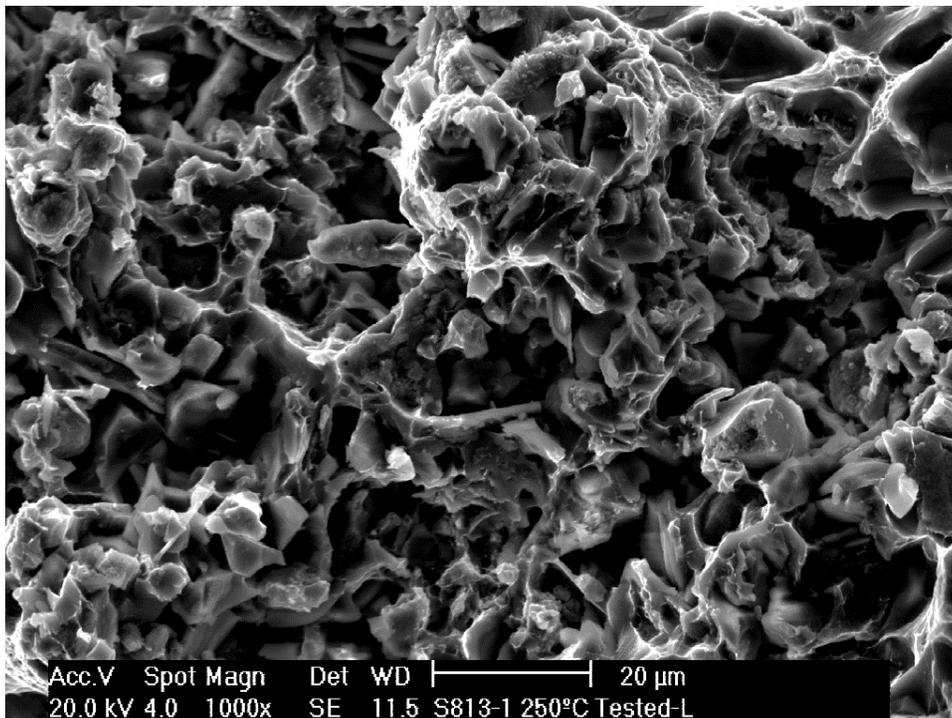
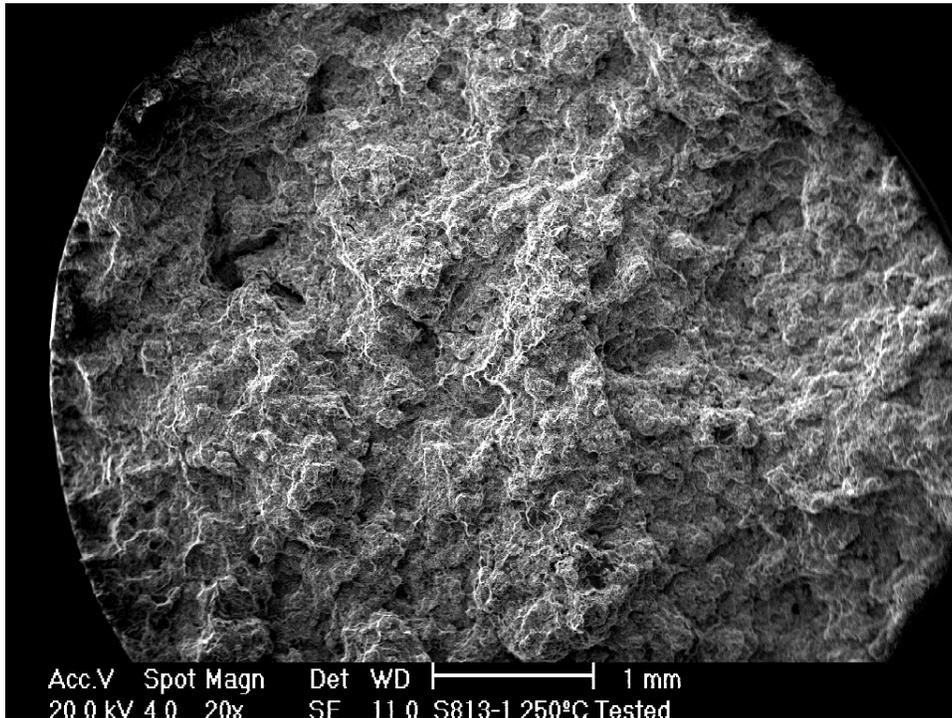


Figure 26: Fracture surface of S813 tensile tested at 250oC.

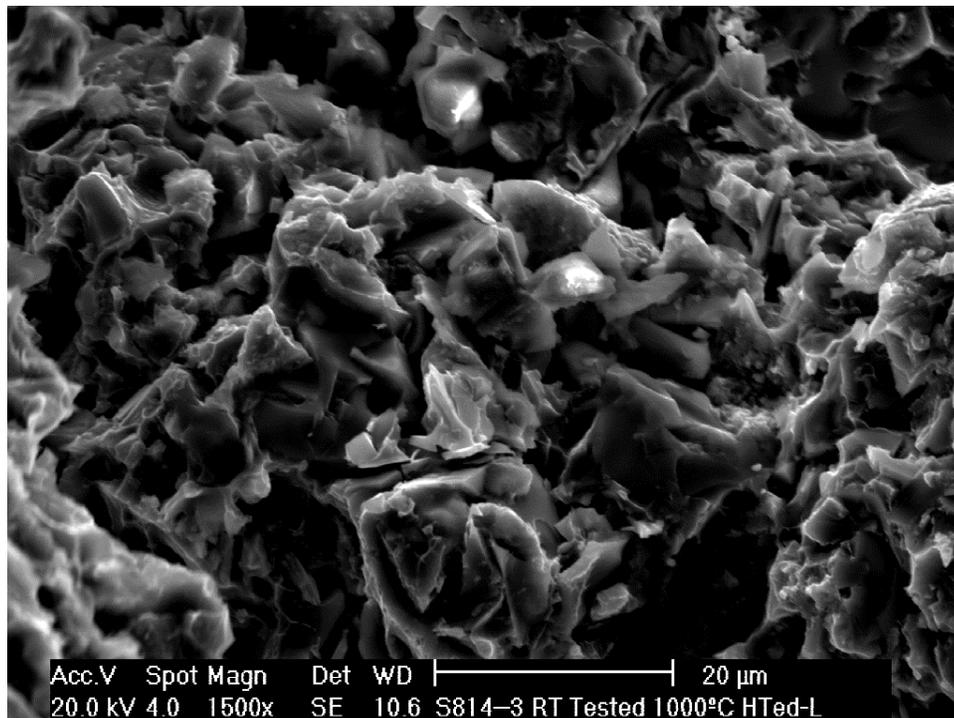
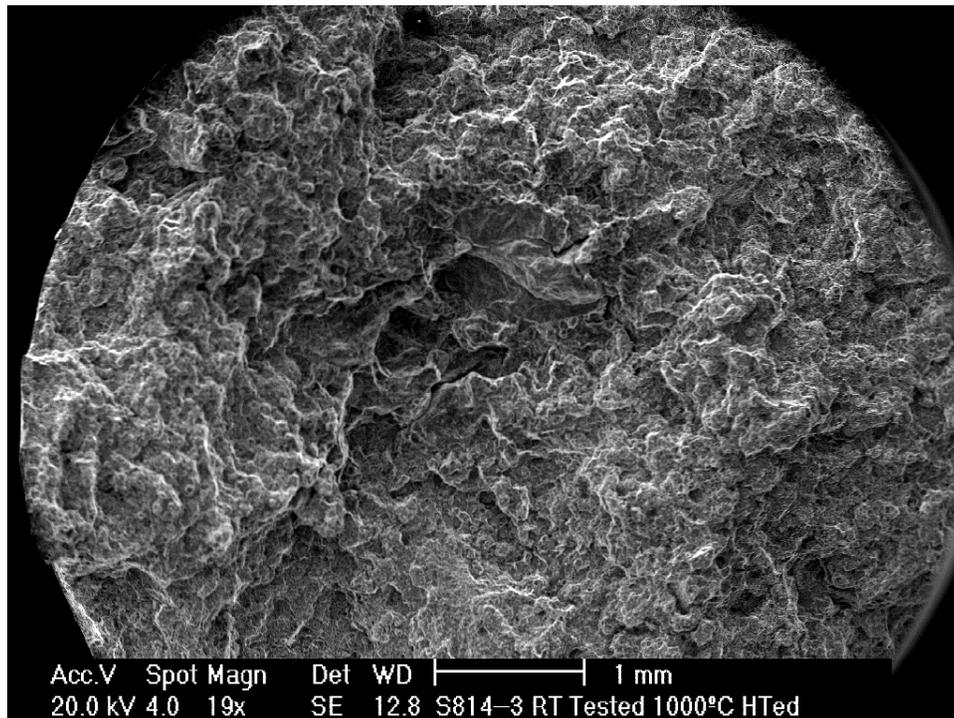


Figure 27: Fracture surface of S814 (250°C for 1000 hrs) tensile tested at room temperature showing quasi-cleavage type failure.

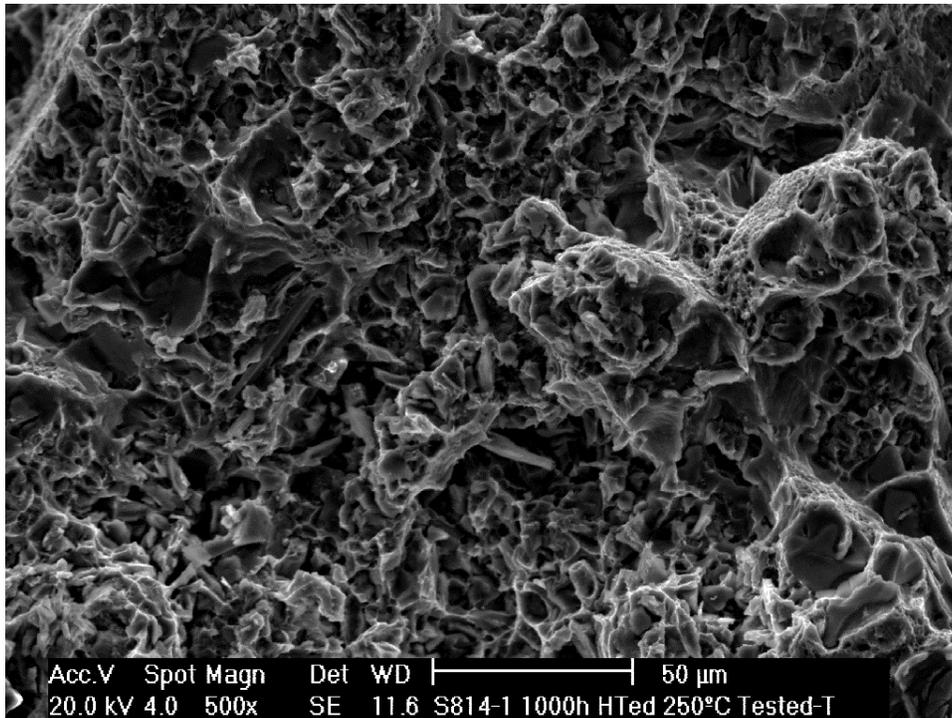
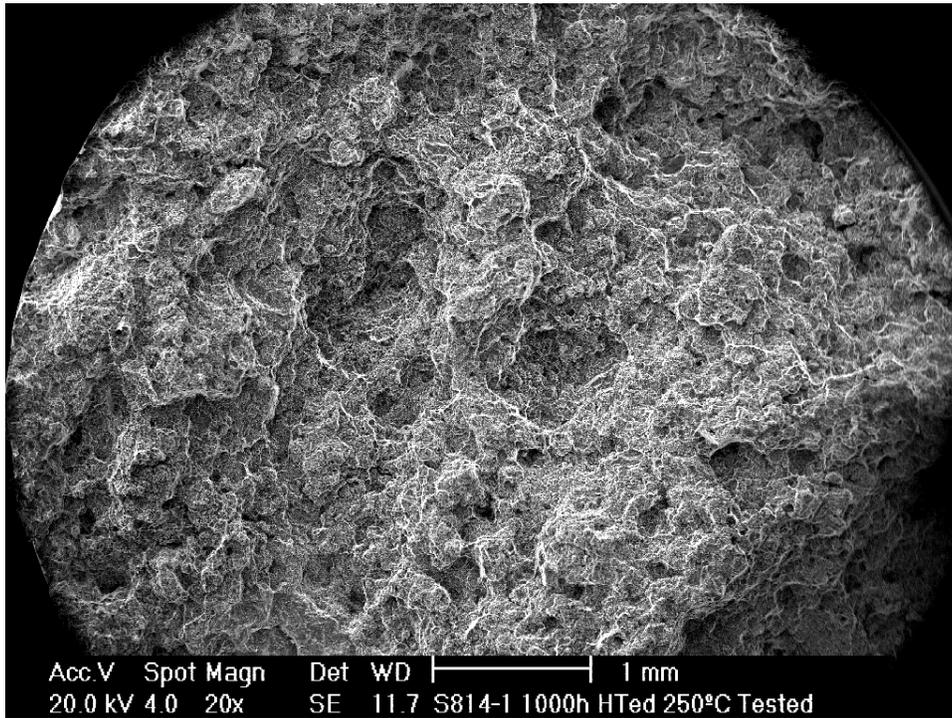


Figure 28: Fracture surface of S814 (250°C for 1000 hrs);

tensile tested at 250°C

3.2 DEVELOPMENT OF MANUFACTURING TECHNOLOGIES

3.2.1 Commercial Alloy Production

Eck Industries worked with KB Alloys (currently AMG Aluminum) for the production of the matrix alloy. KB alloys has significant scalable resources to produce specialized alloys of virtually any chemistry. A 1,000# batch of alloy was produced with the intent of using some of the material to further characterize the matrix with the rest devoted to scale up activity on the composite alloy system.

For the production of the composite alloy system, MC 21 was contacted to determine their interest in manufacturing the composite material based on Eck Industries supplying the AlCuMgSc matrix alloy. MC 21 is known as a high quality metal matrix composites manufacturer, primarily for the electronics industry. The company showed some interest but due to limited capacity at their facility eventually declined a development contract.

Eck Industries then explored in-house production of the composite, potentially through the license of Lanxide technology to produce a pressure-less infiltrated master composite that would then be diluted into the matrix alloy. A number of in-plant trials were performed using this technique. It was determined that the learning curve of this type of master alloy production was too steep, particularly using the alumina selected for the reinforcement and the effort was abandoned.

Eventually REL (Calumet, MI) worked with Eck to produce an aluminum master MMC alloy containing 34 volume percent of alumina particles via pressure infiltration. This master MMC alloy would then be dispersed into the Al₂CuMg_{0.2}Sc alloy melt via standard mixing methods. Melting and mixing trials demonstrated that high volume content alumina particle preforms could be dispersed into an aluminum alloy melt. Melts containing 8 volume percent alumina particles were successfully gravity cast. The alloys for mechanical property and castability testing were prepared using this technique.

Since dispersion costs of master alloys can be significant, Eck opened discussions with AMG Aluminum in 2013 to determine interest in producing the composite alloy in bulk. AMG Aluminum established a business relationship with Thermal Transfer Composites and began working with

them to produce alumina master alloy that they would disperse into the AlCuMgSc matrix alloy. This effort was successful and Eck took delivery of the first fully commercial batch of composite alloy in September 2013. We expect that further development and ongoing production of this alloy will be based on commercial production by AMG Aluminum.

3.2.2 Clean Melting and Mixing Practices

Eck Industries has over 20 years of experience casting metal matrix composite alloys containing ceramic particle reinforcements such as SiC, alumina and nickel coated graphite. Generally, the MMC alloy ingot used to produce cast products was procured from an outside supplier such as Alcan, MC 21 or Inco Limited. This MMC ingot material was subsequently melted and cast into molds to produce castings such as brake rotors, clutch housings and many other geometries. These MMC alloy ingots generally contained 20-30 v/o of reinforcement particles.

Eck industries had planned to use the previously developed melting and stirring techniques for the casting of the AlCuMgSc MMC alloy containing 10 v/o of alumina particles.

Critical aspects of those processes that were investigated include melt processing temperature, stirring, gating system design and alloy fluidity. For the non-composite version of the alloy typical melt practices used for premium aluminum castings were used successfully. The following comments are directed at the composite version of the alloy.

Metal matrix composites containing SiC_p have constrained melting and pouring temperatures due to the potential formation of aluminum carbides which are detrimental to mechanical property and corrosion performance. The melting and pouring temperatures of aluminum alloy MMC alloys containing SiC_p are generally lower than the temperatures normally used for melting and casting of the matrix alloys. The use of alumina particles as a reinforcement allows for the full range of melting and casting temperatures normally used with matrix alloys. The AlCuMgSc MMC alloys were melted and poured at temperatures between 600°-700°C with no detrimental effects to the alloy. These melting and casting temperatures are the same as would be used for melting and casting the matrix alloy.

Alumina (3.95 g/cm³) has a higher density than aluminum (2.70 g/cm³) and needs to be kept in suspension in the melt by stirring continuously with a graphite shaft and impeller. The RPM of the

impeller is chosen to develop some melt movement on the top of the bath but not entrain air and oxides. Exact stirring protocol will vary from furnace to furnace. This is the same protocol as is used in the melting of SiC based composites. Active degassing using fluxes or reactive gasses will de-wet the alumina particles from the melt. The emphasis for this composite was to melt under a protective atmosphere of argon to protect the melt from hydrogen pick-up and from uncontrolled oxide pick-up during the stirring operation.

The gating system is designed to obtain high-volume low-velocity flow of liquid metal into the mold cavity. Metal velocities greater than 0.5 m/s anywhere in the gating system will produce defects. Higher metal velocities are like to entrain air bubbles. When casting MMCs these air bubbles may attach to the particulate reinforcements. This stabilizes the bubble(s) and prevents their collapse. The stabilized bubbles typically become trapped on the top surface of the casting and form porosity defects. These porosity defects are exposed during subsequent processing or machining. The developed matrix alloy is low in Si which reduces fluidity as do the alumina particles. To compensate for this lower fluidity the gating system must be designed to obtain a higher volume metal flow.

A rotary engine end housing (Figure 29) was successfully produced using this alloy.



Figure 29: End housing of rotary engine cast from AlCuMgSc MMC alloy.

A significant amount of casting work was done with the non-composite version of the alloy. Generally the castability of the AlCuMgSc alloy was found to be very similar to that of other Cu containing aluminum casting alloys. Castability is typically defined by three components: fluidity, resistance to hot cracking and pressure tightness. Given each aspect a value from 1 to 5 in decreasing order of performance, Table 20 assesses the castability of the developed AlCuMgSc alloy when compared to other common aluminum casting alloys.

Table 20: Castability comparison of AlCuMgSc with other aluminum alloys.

Aluminum Alloy	Fluidity	Resistance To Hot Cracking	Pressure Tightness
201	3	4	3
242	3	4	4
319	2	2	2
356	1	1	1
AlCuMgSc	3	3	3

A physical example of the excellent castability of the AlCuMgSc alloy is shown in Figure 30. The aircraft cylinder head having a fin-tip thickness of 1.5 mm was successfully produced in this alloy with only minor fin-tip lack of fill.



Figure 30: Air-cooled aircraft engine cylinder head.

3.2.3 Determination of Mechanical and Physical Properties of Developed AlCuMgSc Matrix and MMC Alloys

During the course of this program, a number of mechanical property tests were conducted. The following properties were developed from a 1000 pound prototype heat of the Al₂Cu1Mg0.2Sc matrix alloy at the end of 2008.

Effect of Solidification Rate. The first set of tensile data was used to determine static properties and the effect of solidification rate on tensile properties of the matrix alloy. The as-cast tensile specimens were produced using standard ASTM permanent mold and sand molds. After HIP processing, the specimens were heat treated using a stepped solution treatment of 540°C for 4 hours followed by 560°C for 4 hours. The parts were then aged at 300°C for six hours. The room temperature mechanical properties measured are shown in Tables 21 and 22. With the exception of

the significantly higher elongation values obtained for the permanent mold cast alloy samples, the tensile properties of the two types of castings are very similar.

Table 21: Room Temperature Tensile Properties of Sand Cast AlCuMgSc Alloy.

	Sand Cast		
	Ultimate Tensile Strength, kpsi (MPa)	0.2% Yield Strength kpsi (MPa)	Elongation %
Mean	39.4 (271.7)	26.7 (184.1)	4.5
Median	39.6 (273.0)	26.5 (182.7)	4.5
Standard Deviation	1.3 (9.0)	0.7 (4.8)	0.8
Maximum	41.7 (287.5)	28.4 (195.8)	6.0
Minimum	36.4 (251.0)	25.9 (178.6)	3.0
Range	5.3 (36.5)	2.5 (17.2)	3.0
Calculated Minimum*	35.5 (244.8)	24.6 (169.6)	2.0

Note: * Calculated minimum = Mean – 3(Standard Deviation)

Table 22: Room Temperature Tensile Properties of Permanent Mold Cast AlCuMgSc Alloy.

	Permanent Mold Cast		
	Ultimate Tensile Strength, kpsi (MPa)	0.2% Yield Strength kpsi (MPa)	Elongation %
Mean	40.6 (279.9)	26.2 (180.6)	7.9
Median	40.7 (280.6)	26.0 (179.3)	8.0
Standard Deviation	0.6 (4.1)	0.6 (4.1)	1.0
Maximum	42.2 (291.0)	28.2 (194.4)	9.5
Minimum	39.6 (273.0)	25.4 (175.1)	6.0
Range	2.6 (17.9)	2.8 (19.3)	3.5
Calculated Minimum*	38.9 (268.2)	24.4 (168.2)	4.9

Note: * Calculated minimum = Mean – 3(Standard Deviation)

Optimization of Thermal Treatment Process. The elevated temperature properties of aluminum-scandium alloys are dependent on the incubation and growth of scandium trialuminides. Seidman et al (10) have shown that this mechanism is facilitated at elevated solution heat treatment temperatures, especially for quaternary alloy systems. This optimization experiment was designed

to determine if increasing the solution heat treatment temperature would improve the elevated temperature properties of the developed Al₂Cu₁Mg_{0.2}Sc alloy.

Sand cast tensile bars were heat treated with the two different sets of thermal parameters shown in Table 23. Heat treatment A used the time and temperature parameters developed during Phase 1 of the project. Heat treatment B increases the maximum solution temperature to the highest temperature deemed practical for an Al-Cu alloy. The “stepped” solution treatment is necessary to prevent “burning” of the Al-Cu alloy. Both room temperature and elevated temperature (250°C) tensile properties were accomplished by Westmoreland Mechanical Testing and Research (WMTR). The results of these tests are shown in Table 24. Plots of the data (Figures 31, 32 and 33) illustrate that the higher solution temperature (Heat Treatment B) yields higher elevated temperature properties

This improved thermal treatment was applied to the matrix alloy samples that will be used to determine elevated temperature fatigue properties and all subsequent mechanical properties.

Table 23: Parameters Used to Determine Effect of Solution Treatment

Operation	Heat Treatment A	Heat Treatment B
Solution heat treat and precipitate Al ₃ Sc particles	493°C for 1 hour	493°C for 1 hour
	510°C for 1 hour	510°C for 1 hour
	532°C for 1 hour	532°C for 1 hour
	560°C for 5 hours	560°C for 1 hour
		588°C for 4 hours
Hot water quench	89°C	68°C
Grow size of particles	300°C for 6 hours	300 °C for 6 hours

Table 24: Effect of Solution Treatment Temperature on Tensile Properties.

	Test Temperature °C	Solution Treatment A			Solution treatment B		
		Ultimate Strength, MPa	Yield Strength, MPa	Elong, %	Ultimate Strength, MPa	Yield Strength, MPa	Elong, %
Mean	20	250.1	140.4	6.5	249.4	151.2	5.8
Std. Dev.		1.7	1.1	1.0	4.7	20.3	0.8
Max.		251.7	141.3	7.5	253.0	171.7	6.5
Min.		248.2	139.3	5.5	244.1	131.0	5.0
Separator							
Mean	250	114.9	89.2	37.5	122.5	91.2	30.0
Std. Dev.		1.6	6.6	3.5	6.2	6.3	4.0
Max.		115.8	95.8	41.5	129.6	97.9	34.5
Min.		113.1	82.7	35.0	118.6	85.5	27.0

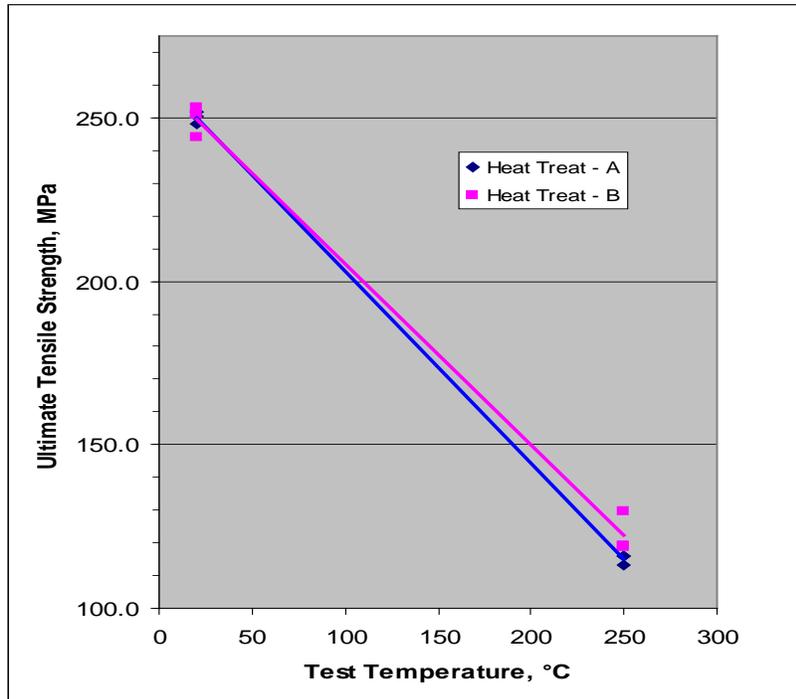


Figure 31: Ultimate Strength of Matrix Alloy as Function of Solution Treatment.

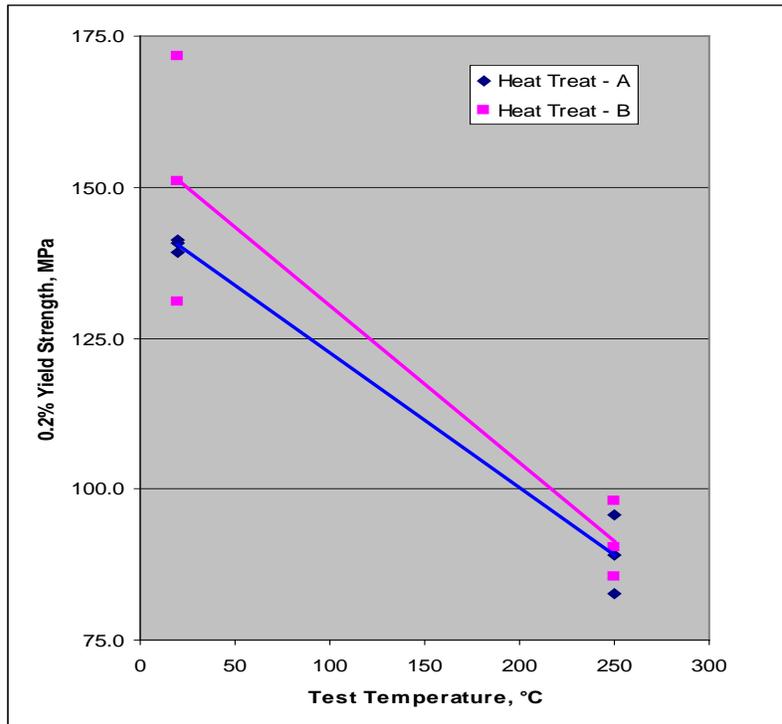


Figure 32: Yield Strength of Matrix Alloy as Function of Solution Treatment.

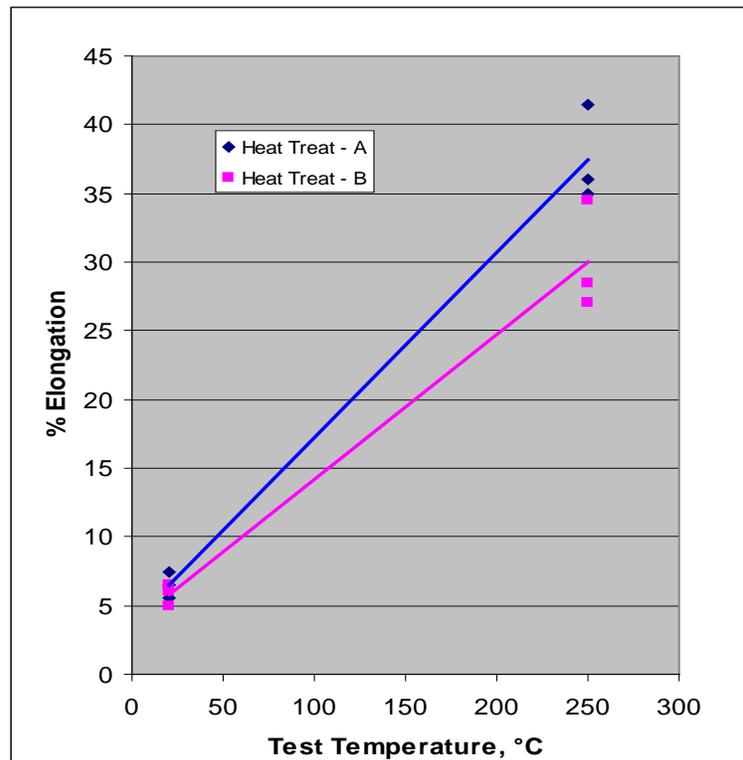


Figure 33: Percent Elongation of Matrix Alloy as Function of Solution Treatment.

Additional sand cast and HIP'd ASTM tensile bars made from the Al₂CuMg0.2Sc matrix alloy were heat treated (Heat Treatment B) and shipped to Westmoreland Mechanical Testing and Research (WMTR) for determination of elevated temperature properties. Stress Life fatigue data at a test temperature 200°C and an R-ratio of -1 indicates a fatigue strength of 78.6 MPa (11.4 ksi).

A second set of data was determined for specimens processed in the same manner but after exposed in air to a temperature of 260°C for 10 hours. The room temperature tensile properties of these specimens are shown in Tables 25 and 26. With the exception of the significantly higher elongation values obtained for the permanent mold cast alloy samples, the tensile properties of the two types of castings are very similar. Stress Life fatigue data from this second set of specimens at a test temperature 200°C and an R-ratio of -1 indicated a fatigue strength of 11.4 ksi. Note that the ultimate and yield strength values seem to be independent of the type of casting process used. However, the type of casting process used does appear to have a significant effect on ductility.

Table 25: Room Temperature Tensile Properties of Sand Cast Matrix Alloy after 260°C Exposure in Air for 10 Hours.

	Ultimate Tensile Strength, MPa	0.2% Yield Strength MPa	Elongation %
Mean	39.4	184.1	4.5
Std. Dev.	1.3	(4.8	0.8
Maximum	41.7	195.8	6.0
Minimum	36.4	178.6	3.0

Table 26: Room temperature tensile properties of permanent mold cast matrix alloy after 260°C exposure in air for 10 hours.

	Ultimate Tensile Strength, MPa	0.2% Yield Strength MPa	Elongation %
Mean	279.9	180.6	7.9
Standard Deviation	4.1	4.1	1.0
Maximum	291.0	194.4	9.5
Minimum	273.0	175.1	6.0

A potential customer for Al₂CuMg0.2Sc castings is generating fully reversed (R = -1) room temperature fatigue life data for cast and heat treated specimens that have seen prior exposure at elevated temperatures. The customer provided the data shown in Table 27. These data are for specimens previously exposed to temperatures of 260°C and 315°C for the times shown in the table. The stress level used for the tests (110 MPa [16 ksi]) is greater than the room temperature fatigue strength of most aluminum alloy castings. The results encouraged the customer to continue development efforts with this alloy system.

Table 27: Room Temperature Fatigue Life (R=-1) after Elevated Temperature Exposure of Cast and Heat Treated AlCuMgSc at a Stress Level of 110 Mpa (16 ksi).

Exposure Temperature, °C	Exposure Time, hours	Average Cycles to Failure (3 tests)
260	100	803,000
315	10	450,000
315	100	360,000

The metal matrix composite alloy used for this development effort contained 10 volume percent of nominally 8 micron diameter alumina particles. Standard ASTM sand cast specimens were produced from this alloy, heat treated using the same parameters as used for the matrix alloy. Tensile properties were determined at room temperature, 20° and 250°C. These are listed in Table 28. While the room temperature properties for the composite alloys are slightly lower than those for the matrix alloy, the high temperature strength is about 13% higher.

A primary market for the composite alloy may be aircraft cylinder heads which see routine temperature excursions from -40°C to 210°C. The customer requested confirmation of room temperature properties using identical testing as the samples done at -40 and 210C. That confirmation room temperature testing was within the test data shown above, at 230.3 MPa (33.4 ksi) tensile, 173.8 MPa (25.2 ksi) yield and 2% elongation.

**Table 28: Mechanical Properties of Sand Cast Al₂Cu₁Mg_{0.2}Sc -10 v/o Al₂O₃_p
Metal Matrix Composite Alloy.**

	Test Temperature, °C	Tensile Strength MPa (ksi)	0.2% Yield Strength MPa (ksi)	Elongation %
Average	20	228.2 (33.1)	161.3 (23.4)	2.6
Std. Dev.		15.9 (2.3)	15.2 (2.2)	0.7
Maximum		251.0 (36.4)	182.0 (26.4)	4.0
Minimum		206.9 (30.0)	20.9 (144.1)	2.0
<hr/>				
Average	250	139.3 (20.2)	104.1 (15.1)	8.9
Std. Dev.		8.3 (1.2)	.41 (0.6)	3.6
Maximum		148.2 (21.5)	110.3 (16.0)	15.5
Minimum		126.2 (18.3)	97.9 (14.2)	5.0

Physical Properties

Density of Matrix Alloy. The immersion density method (Archimedes Method) was used to determine the specific density of the AlCuMgSc matrix alloy. Six samples were cast from a single heat of the matrix alloy and hot isostatically pressed (HIP'd) to full density. The chemistry of this particular heat of matrix alloy is shown in Table 29. The density of the alloy was statistically determined to be 2.753 grams per cubic centimeter. The results for each sample are provided in Table 30

Table 29: Chemical analysis of matrix alloy heat used to determine its theoretical density.

Heat Number	Chemistry, weight %							
	Cu	Mg	Mn	Ni	Si	Sc	Fe	Al
130604	2.2	1.0	0.52	0.52	0.54	0.20	0.04	remainder

Table 30 - Results of immersion density test for AlCuMgSc matrix alloy.

Sample Number	Density, grams/cc
1	2.749
2	2.740
3	2.760
4	2.758
5	2.750
6	2.762
Mean Value	2.753
Standard Deviation	0.008

Coefficient of Thermal Expansion. A working value for the CTE (coefficient of thermal expansion) was determined for Al₂Cu₁Mg_{0.2}Sc MMC containing 7 v/o of nominally 8 micron diameter alumina particles. Cast and HIP'd bars of the MMC were turned; stabilized at a temperature of 21°C (70° F) and their length measured. The 5.7846-cm (2.2774-inch) long bars were then heated to a temperature of 210°C (410°F). The temperature was verified via an embedded thermocouple. The length of the bars, at temperature, was 5.8075 cm (2.2864 inches). This gives a measured linear CTE of 12.1 μ/cm/°C (11.6μin./in/°F) over the given temperature range. For reference this compares to 13.7 μ/cm/°C (13.1μin./in/°F) for alloy 242.

4.0 BENEFITS ASSESSMENT

The objective of this project was to provide a production capable cast aluminum MMC alloy with an operating temperature capability of 250-300°C. Important industrial sectors as well as the military now seek lightweight aluminum alloy castings that can operate in temperature ranges of

250 to 300°C. Current needs in this temperature range are being satisfied by the use of titanium alloy castings. These have the desired strength properties but the end components are heavier and significantly more costly. Also, the energy requirements for production of titanium alloy castings are significantly higher than those required for production of aluminum alloys and aluminum alloy castings.

The metal casting industry is one of the most energy-intensive manufacturing sectors with the melting process accounting for 55-72% of its energy consumption.^{19, 20} . However, the most significant energy usage in titanium manufacturing is the energy used in metal refining. While it is difficult to project market share and the full cost of titanium manufacture, the following analysis seems reasonable given the available data.

In 2003, 40,977 tons of titanium castings were shipped²⁰. If we assume that the aluminum alloys developed under this program can penetrate 10% of that market, 4,000 tons of high temperature AlCuMgSc castings would be produced. To determine the amount of energy saved by replacing 4000 tons of Ti alloy castings we focused only on the energies used in (1) the production of the primary titanium needed to produce 4000 tons of Ti alloy castings, (2) the production of the primary aluminum needed to produce 4000 tons of the elevated temperature capable AlCuMgSc alloy castings, and (3) the melting energies needed to melt and cast the two alloys into 4000 tons of castings. The energies necessary to accomplish these operations are listed in Table xx. This first level energy requirement calculation shows an energy savings of 532 million BTU per ton of Ti alloy castings replaced by the developed elevated temperature capable AlCuMgSc alloy. This is a 77% savings in energy requirements!

Table 31: Energy Savings Obtained if Ti Alloy Castings are replaced with AlCuMgSc Castings

Operation	Quantity, Tons	Energy Required, Million BTU
Energy to produce Ti needed to make 4000 tons of Ti alloy castings (a)	5880	2,487,420
Energy for making Ti castings (b)	4000	260,000

Total energy for making Ti castings	4000	2,747,240
Energy to produce primary Al needed to make 4000 tons of Al castings (c)	5520	220,800
Energy for making Al castings (d)	4000	397,600
Total energy for making Al castings	4000	618,400
Total energy savings when AlCuMgSc castings replace Ti castings	4000	2,128,884
% total energy savings when AlCuMgSc castings replace Ti castings	4000	77 %

Notes: a. Assumes a 47% yield and scrap loss²⁰.

b. Reference 20

c. Assumes a 38% yield and scrap loss²⁰

d. Reference 20

5.0 COMMERCIALIZATION

For our typical customer base the acceptance of new cast alloy systems depends on its *Performance*, its *Price* with respect to those of competitive alloy systems, its commercial *Availability*, and the availability of national and/or international *Reference Standards*

The *Performance* capability of the AlCuMgSc alloy system and its metal matrix composite (MMC) derivative is discussed in detail in this report. Eck Industries, Inc. has worked with three different domestic and international customers to assess technical needs and produce prototype parts for testing. These parts are for customers in aviation, ventilation and stationary power generation. All of these applications require weight minimization and the ability to perform at operating temperatures of 250°C. Ti alloy castings such as Ti-6-4 are an alternative at much higher cost and component weight. As of the date of this report, all three of those customers plan to move forward based on alloy performance, assuming the other commercialization metrics are met.

Commercial *Pricing* of the AlCuMgSc alloy and its MMC derivative is yet to be established. The MMC alloy contains scandium and alumina particulates which implies a price delta versus standard casting alloys of about \$5.00 per pound. This is equivalent to the price of the silver containing aluminum alloy 201 but is significantly less costly than titanium alloys.

To establish commercial *Availability* of this elevated temperature capable casting alloy system, the project team has worked with AMG Aluminum and Thermal Transfer Composites to develop a commercial production base. Phase 2 of our development effort has established that the best ,both technically and financially, approach to the commercial production of the MMC alloy is to blend a master alumina/aluminum composite with the AlCuMgSc casting alloy. Thermal Transfer Composites will use well established commercial practices to produce the master alumina/aluminum composite. AMG Aluminum, a world-leading provider of master alloys and grain refiners for the aluminum industry, will produce the AlCuMgSc casting alloy and will blend the master alumina/aluminum master alloy with the AlCuMgSc alloy to produce the AlCuMgSc MMC casting alloy. AMG has confirmed that production capacity of at least 4000 tons/year is currently in place and more can be added if required.

As part of this development effort, proposed SAE AMS standards for the AlCuMgSc casting alloy and its derivative MMC alloy have been written (see Appendices B and C of this report). SAE has been contacted to initiate discussion to establish standards documents for the two alloys.

The two papers listed below which chronicle the development of the AlCuMgSc matrix alloy have already been presented and published. In addition, a series of presentations

1. “Development of an Aluminum Alloy for Elevated Temperature Applications”, K. Sadayappan, G. Gegel, D. Weiss & M. Sahoo, Shape Casting: The 3rd International Symposium, Ed. by J. Campbell, P. Crepeau & M. Tiryakioglu, TMS, 2009,
2. “Development of Cast Al Alloys for Elevated Temperature (250°C) Service”, D. J. Weiss, G.A. Gegel, & K.S. Sadayappan, Proceedings of American Foundry Society, April 2011.

designed to emphasize the capabilities of both the AlCuMgSc alloy and its metal matrix composite (MMC) derivative to a larger audience has been planned. An abstract submitted to MS&T 14 has been accepted for presentation at the October, 2014 conference sponsored by ASM International, The American Ceramics Society (ACerS), The Association for Iron & steel Technology (AIST) and TMS (The Minerals, Metals and Materials Society). Additional presentations will occur in 2015. A series of articles for the technical trade press will be developed starting in the spring of 2015.

6.0 ACCOMPLISHMENTS

1. An aluminum alloy capable of maintaining strength at high temperatures, up to 250°C, was developed. This alloy contains copper, magnesium, silicon, nickel, manganese and scandium as alloying additions. This alloy composition is amenable to casting using either sand or permanent molds.
2. Tensile test results indicate that the elevated temperature (250°C) properties of the matrix alloy are 3.6 times higher than those of wrought aluminum alloy 2618-T6. When compared to a cast aluminum alloy (354-T6) generally used for turbine compressor wheels, the matrix alloy properties are 2.1 times higher.
3. Alumina (Al_2O_3) particulates are a suitable reinforcement for improving the high temperature properties of the developed AlCuMgSc alloy from both a cost and fabrication standpoint.
4. In Phase 1 of the program a 2 step (X + Y) stir casting process was developed for the fabrication of $\text{Al}_2\text{O}_3/\text{Al}$ composite using the developed Al-Cu-Mg-Sc elevated temperature capable alloy.
5. A heat treatment schedule for both the AlCuMgSc matrix alloy and the AlCuMgSc-(Al_2O_3)_P composite alloy this alloy was developed.
6. An improvement in modulus, tensile strength and yield strength of AlCuMgSc alloy was achieved by the addition of Al_2O_3 powder to form an $\text{Al}_2\text{O}_3/\text{Al-Cu-Mg-Sc}$ composite. Alloy.
7. Developed clean melting and mixing practices and successfully used them to produce prototype components in both sand and permanent molds.
8. Working with MC-21 and AMG Aluminum established commercial practices for production of the AlCuMgSc alloy and its MMC variant.
9. Determined ambient and elevated temperature static and dynamic properties for the AlCuMgSc alloy and its MMC variant. Physical properties needed for design of cast products were measured.

10. Drafted AMS specifications for AlCuMgSc alloy castings and AlCuMgSc MMC alloy castings.

7.0 CONCLUSIONS

1. The developed AlCuMgSc alloy extends the operational temperature capability of AlCu casting alloys to 250°C. The manufacture of castings from this alloy instead of the currently used Ti alloy castings would reduce manufacturing costs and reduce energy requirements.
2. The additional strength (about 14%) attained by the MMC version of the developed alloy system would allow even greater penetration of the applications currently manufactured from Ti alloy castings. The result would be even greater reductions in manufacturing costs and energy requirements.
3. Equivalent or better castability of the developed alloy as compared to currently used A201 and A206 aluminum castings may reduce manufacturing costs for the more difficult part configurations.

8.0 RECOMMENDATIONS

The following additional work is recommended to further optimize the alloy:

- 1) Investigate longer aging times to see if additional high temperature strengthening phases can be precipitated.
- 2) Investigate replacing a portion of the scandium with zirconium or adding nickel to reduce alloy cost.
- 3) Investigate smaller particle size for the alumina to improve strength at both room and elevated temperature.
- 4) Due to the strong effect of alumina on elevated property strength, investigate higher alumina contents, perhaps as a substitute for some of the scandium.

9.0 REFERENCES

1. ASM Handbook Vol. 2 Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Published by ASM International, 1990, pp 125, 173-175.
2. Aluminum Alloy RR350 reference. Private Communication
3. NASA 388 Material Properties Data Sheet, NASA-Marshall Space Flight Center, Metallic Materials & Processes Group (ED33), Huntsville, AL 35812.
4. Granger, D. A., Truckner, W. G. and Rooy, E. L., "Aluminum Alloys for Elevated Temperature Application", AFS Transactions, Vol. 143, 1986, pp. 777-784.
5. Crepeau, P. N., Antolovich, S. D., and Worden, J. A., "Structure-Property Relationships in Aluminum Alloy 339-T5: Tensile Behavior at Room and Elevated Temperature", AFS Transactions, Vol. 148, 1990, pp. 813-822.
6. Gundlach, R. B., et al., "Thermal Fatigue Resistance of Hypoeutectic Aluminum Silicon Casting Alloys", AFS Transactions, Vol. 141, 1994, pp. 205-223
7. Komiyama, Y., Uchida, K., and Gunshi, M., "Effects of Fe, Ni, Mn, Cr, and Mg on Properties of Ni free aluminum casting alloy for piston", J. Japan Inst. Light Metals, Vol. 28, No. 8, 1978, pp. 377-382.
8. Catherall, J. A., and Smart, R. F., "The Effects of Nickel in Aluminum-Silicon Eutectic Alloys", Metallurgia, 78-79, June 1969, pp. 247-250.
9. Soave, R., Feran, G., Leites, J., Kuhn, C. and Gegel, G., "Development of a Fiber Reinforced Aluminum Piston for Heavy Duty Diesel Engines", SAE Paper No. 940584, SAE International, March 1994.
10. Seidman, D.N. et al, "Precipitation strengthening at ambient and elevated temperatures of heat treatable Al(Sc) alloys, Acta Materialia, Vol. 50, 2002, pp.4021-4035.
11. Zakharova V.V and Rostova T.D., "On the possibility of scandium alloying of copper-containing aluminum alloys", Metal Science and Heat Treatment, Vol. 37, Nos. 1-2, 1995, pp. 65-69.
12. Nakayama, M. and Miura, Y., "The effect of scandium on the age-hardening behavior of Al-Cu alloy", Proceedings, 4th. International Conference on Aluminum Alloys (1994), pp. 538-545.
13. Li Yu, W. et al, "Mechanical properties and microstructures of alloy 2618 with Al₃(Sc, Zr) phases", Materials Science and Engineering, A368, (2004), pp. 88-93.

14. Paris, H.G., Sanders, T.H. and Riddle, Y.W., "Assessment of Scandium Additions in Aluminum Alloy Design", Proceedings, 6th. International Conference on Aluminum Alloys (1998), pp. 219- 224.
15. C. Fuller, D.N. Seidman, D.C. Dunnand, "Creep Properties of Coarse Grained Al(Sc) Alloys at 300°C", Scripta Materialia, 40, 6, 691-696 (1999).
16. Y. Harada, D.C. Dunand, "Creep Properties of Al₃Sc and Al₃(Sc, X) Intermetallics", Acta Materialia, 48, 3477-3487 (2000).
17. H.L. Cox, Br. J. Appl. Phys. Vol. 3, 1952, p. 72.
18. D.B. Marshall, N. Tatsuo and A.G. Evans, Amer. Ceram. Soc., 1982, C-175
19. Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry. BCS Incorporated, 2005
20. Theoretical Best Practice Energy Use in Metalcasting Operations, Keramida Environmental, 2004
21. A Critical Evaluation of Processes to Produce Primary Titanium, DS Vuuren, The Journal of The South Africa Institute of Mining and Metallurgy, August 2009

10.0 APPENDICES

APPENDIX A – Microstructural Evaluation

Four alloys were selected for detailed microstructural analysis. The composition of the selected alloys is presented in Table 1. Alloy 1 is the commercially available A206 alloy. All the alloys were heat treated. Also some of the samples were held at 250°C for 1000 hours. The thermal cycles seen by each alloy evaluated are presented in Table 2. The hardness values of the selected samples are presented in Table 3.

Table 1. Alloy compositions

Alloy Number	Weight Percent					
	Cu,	Mg	Si	Ni	Mn	Sc
1	5.10	0.35				
10	2.20		0.43	0.47	0.48	0.25
13	1.99	0.98	0.47	0.55	0.23	0.17
15	1.91	0.92		0.52	0.48	0.16

Table 2. Heat Treatment Cycles

Alloy No.	Two-Step Heat Treatment		Warm Water Quench	Ageing	Exposure
	Step 1 Anneal	Step 2 Solution			
1	490°C; 2 hrs	525°C; 14 hrs	80°C	210°; 8 hrs	--
10	490°C; 2 hrs	525°C; 14 hrs	80°C	300°C; 10 hrs	250 °C; 1000 hrs
13	490°C; 2 hrs	560°C; 4 hrs	80°C	300°C; 6 hrs	250 °C; 1000 hrs
13A	490°C; 2 hrs	590°C, 4 hrs	80°C	300°C; 6 hrs	250 °C; 1000 hrs
15	490°C; 2 hrs	560°C; 4 hrs	80°C	300°C; 6 hrs	250 °C; 1000 hrs
15A	490°C; 2 hrs	590°C; 4 hrs	80°C	300°C; 6 hrs	250 °C; 1000 hrs

Table 3. Hardness Values of Alloys after various thermal treatments.

Alloy	As Cast	As Heat Treated (see Table 2)	After Exposure at 250°C for 1000 hours
	B H	BHN	BHN

	N		
1	74	102	--
10	62	63	62
13	83	77	71
13a	83	84	80
15	79	76	75
15a	79	80	75

METALLOGRAPHIC RESULTS

As-cast microstructures (Figures 1 - 4 and Table 4)

- The as-cast structures contain the Cu_2Al eutectic along with other precipitates. All four alloys show essentially the same eutectic structure and grain size.
- Alloys 10, 13 and 15 contain at least five precipitates along the grain boundaries and interdendritic areas not seen in alloy 1. See Figures 2 and 3. An EDS analysis of these particles, as observed in alloy 15, is presented in Table 4.
- The particle containing Cu, Ni and Sc, particle number 4 shown in Figure 3, is important because it shows that some of the Sc has tied up with Cu and Ni as shown in Figure 4. The presence of this type of particle even after thermal treatment and long term exposure at 250°C indicates that these particles are very stable.

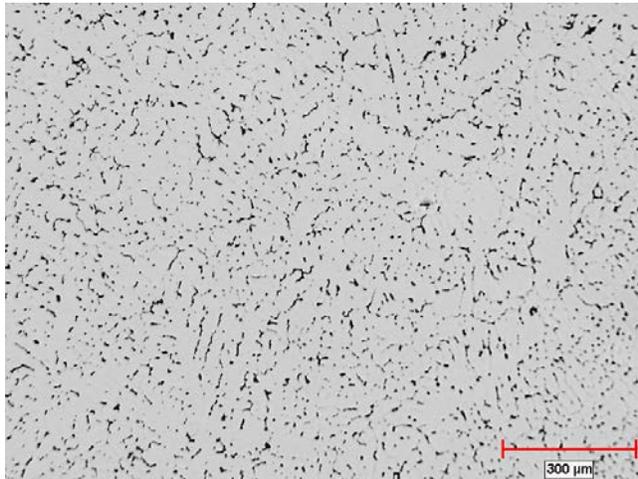
Heat treated structure (After ageing treatment; Figures 5 - 10 and Table 5)

- The Cu_2Al eutectic, observed in interdendritic areas and grain boundaries of as-cast structure, completely dissolves in the matrix during solution treatment.
- The precipitation of these Cu_2Al particles in the matrix after heat treatment is shown in Figure 7. All these alloys are in overaged condition.
- Alloys 10, 13 and 15 reveal some particles remain in the grain boundaries without dissolution during heat treatment. As shown in Table 5, most of these precipitates contain Ni.
- The feathery precipitate shown in Figures 8b and 9b contain Cu, Ni and Sc. These particles are analyzed using EDS and identified as numbers 4 and 7 in Figure 10.

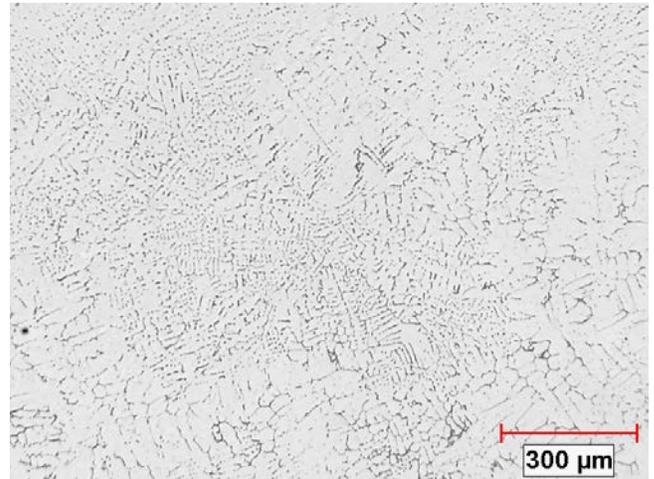
After 1000 hr Exposure at 250°C (Figures 11 - 13 and Table 6)

- Even after long term exposures the nickel containing particles are very stable
- The feathery particle containing Sc can be observed in Figure 13 (particle 4).

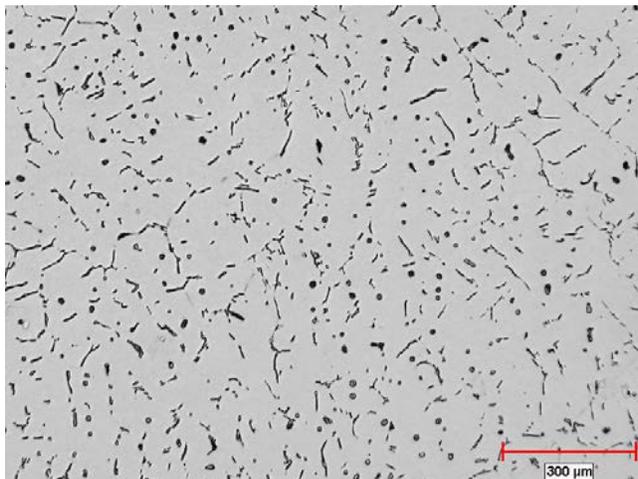
The significance of this particle containing Sc, Ni and Cu is two-fold. First; this Sc is not be available to form trialuminide particles. However, the presence of these micron sized phases even after extended time at 250°C demonstrates their thermal stability. Expectedly, these are acting as phases that provide elevated temperature strengthening to the alloy.



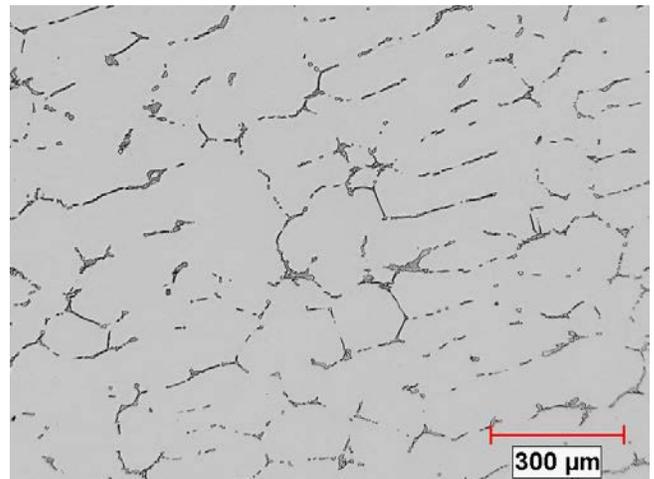
Alloy 1



Alloy 10



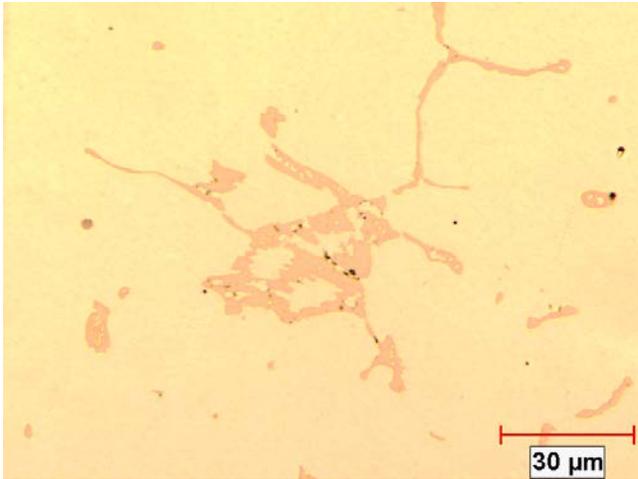
Alloy 13



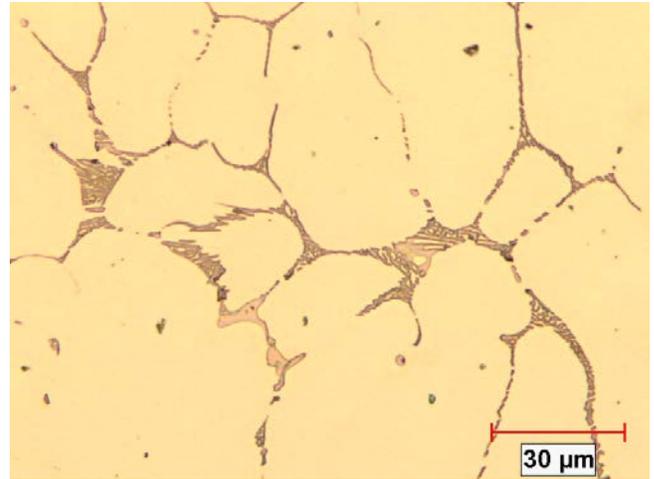
Alloy 15

Figure 1 – Micrographs in as-cast condition.

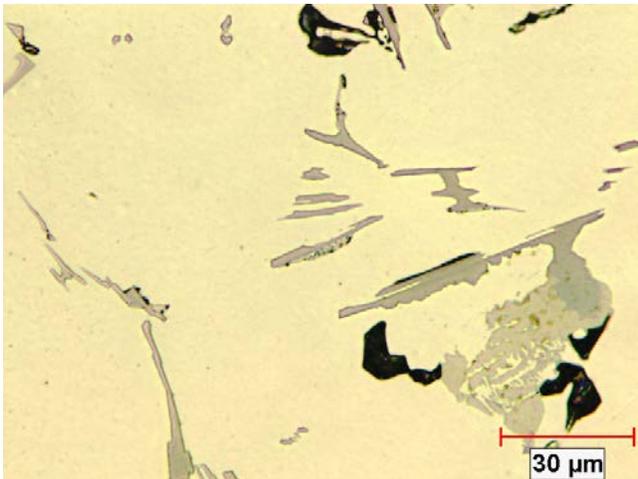
Unetched; 50X magnification.



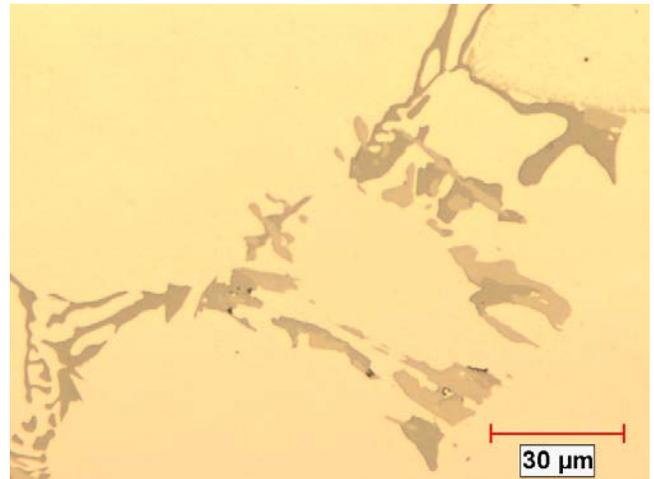
Alloy 1



Alloy 10



Alloy 13



Alloy 15

Figure 2 - Micrographs in as-cast condition.

Unetched, 500X magnification

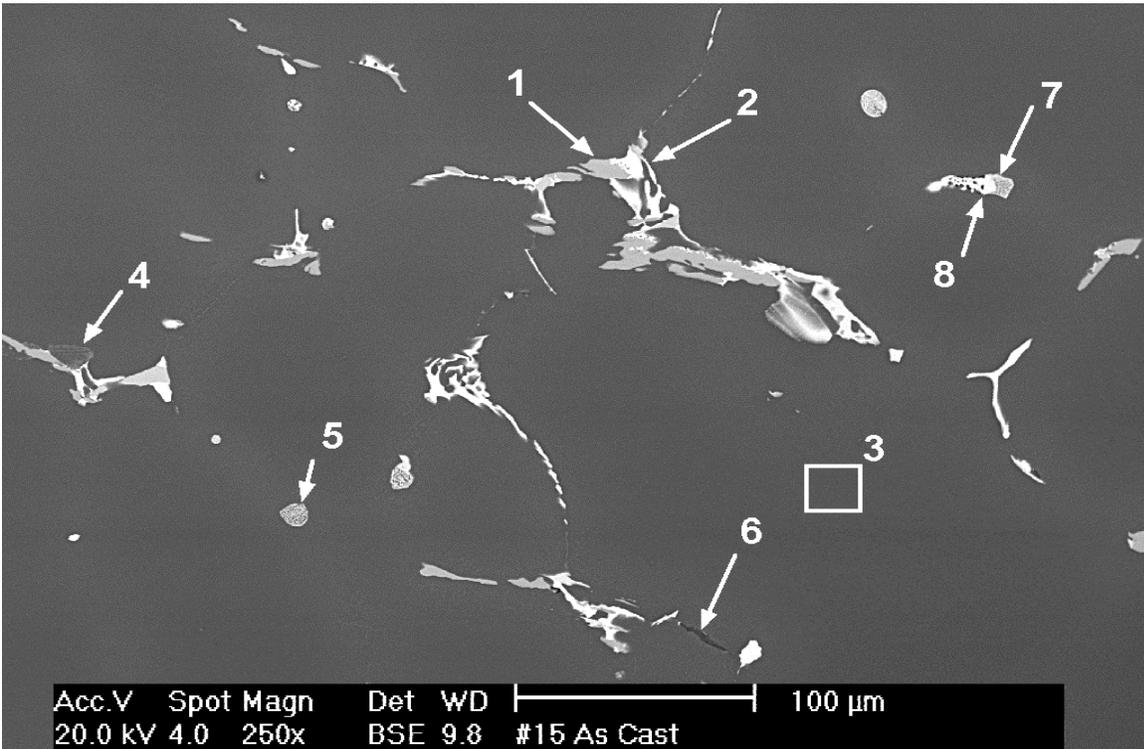
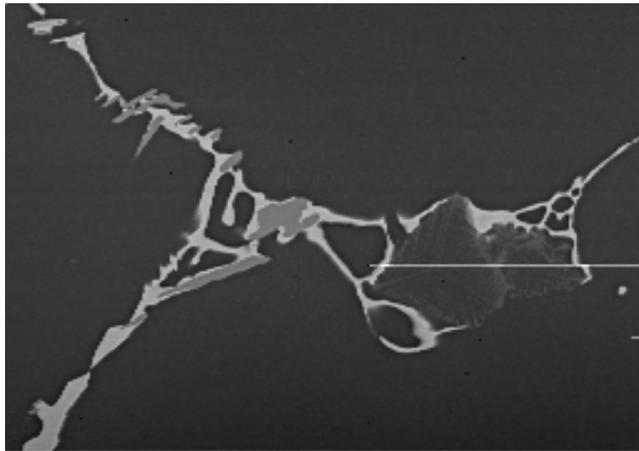


Figure 3 - SEM micrograph showing the particles in alloy 15 in as-cast condition

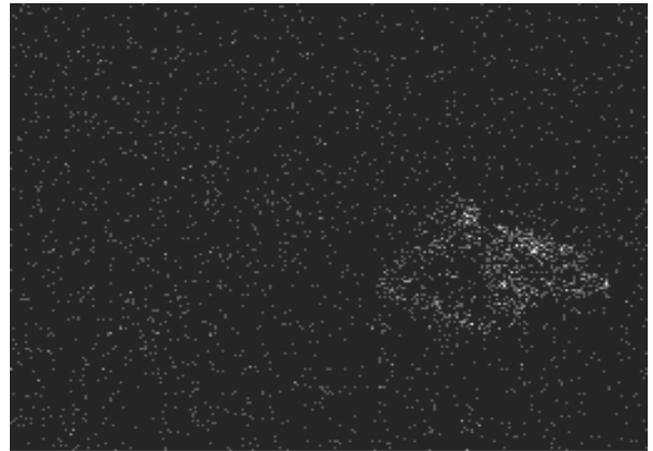
Table 4- Phase constituents in the as-cast alloy 15

Phase	Al	Cu	Mg	Si	Ni	Mn	Sc	Fe
1	x	x			x	x		x
2	x	x			x			
3	x	x	x					
4	x	x	x		x		x	
5	x	x	x	x	x	x		
6	x	x	x	x				
7	x	x	x					
8	x	x	x					



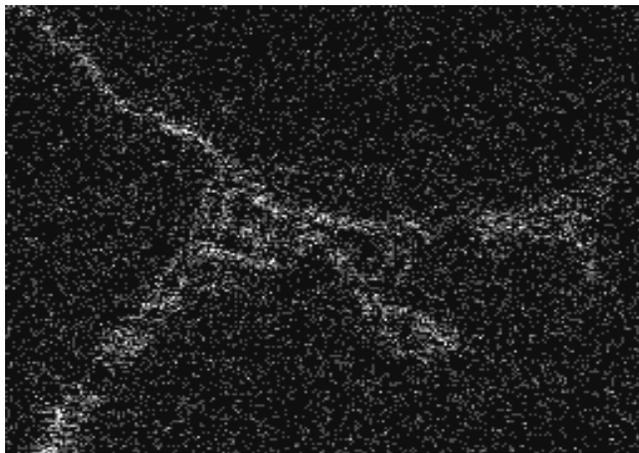
← 50 um →

a) SEM Image of Sc rich precipitate



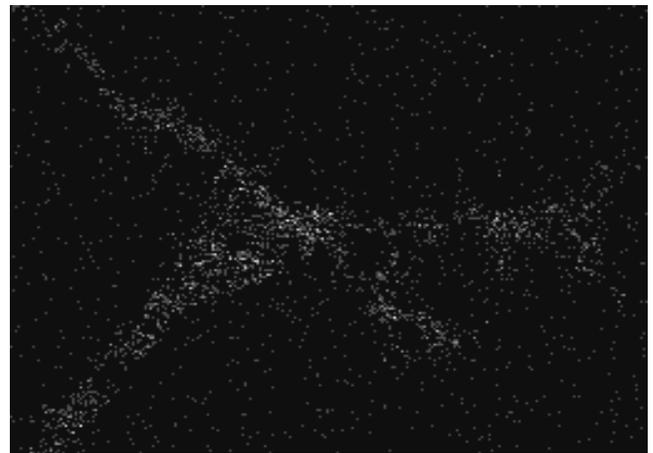
← 50 um →

b) Sc distribution



← 50 um →

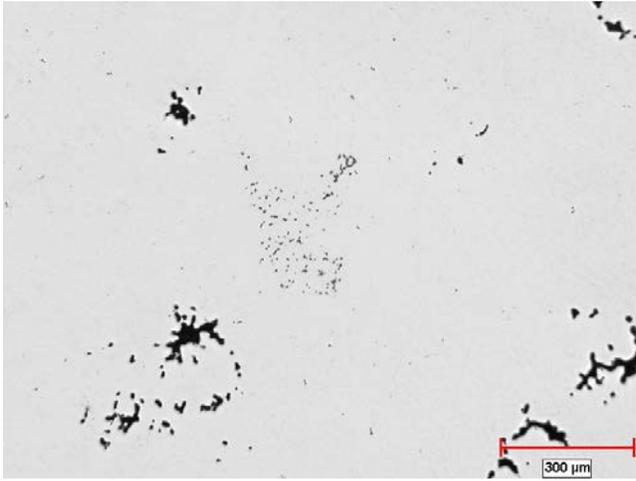
c) Cu distribution



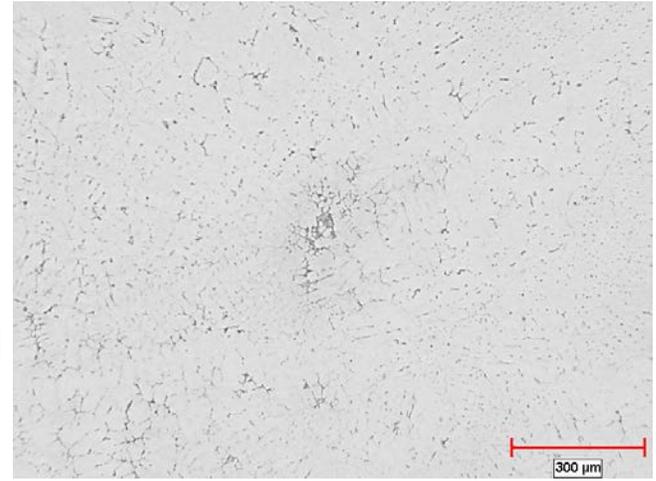
← 50 um →

d) Ni distribution

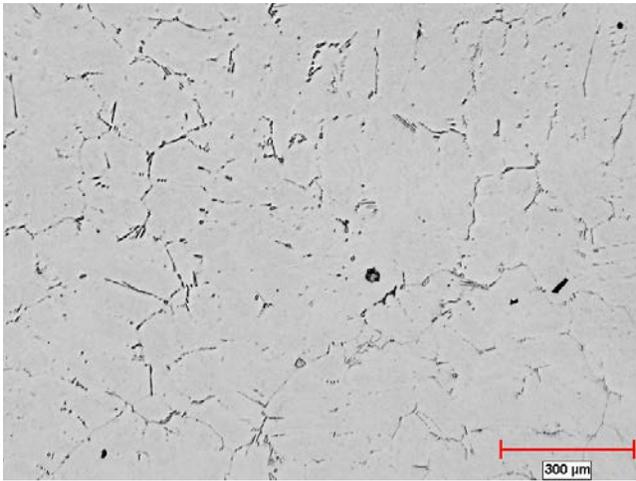
Figure 4 - EDS mapping of particle in as-cast alloy 15. This particle is identified as # 4 in Figure 3



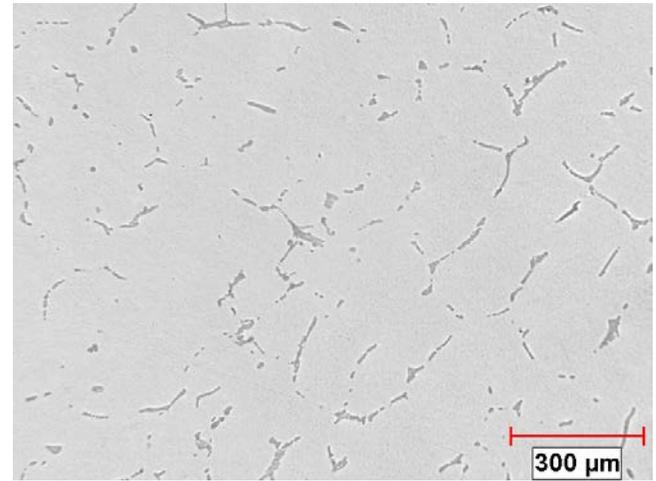
a) Alloy 1, aged at 210°C for 8 hrs



b) Alloy 10, Aged at 300°C for 10 hrs



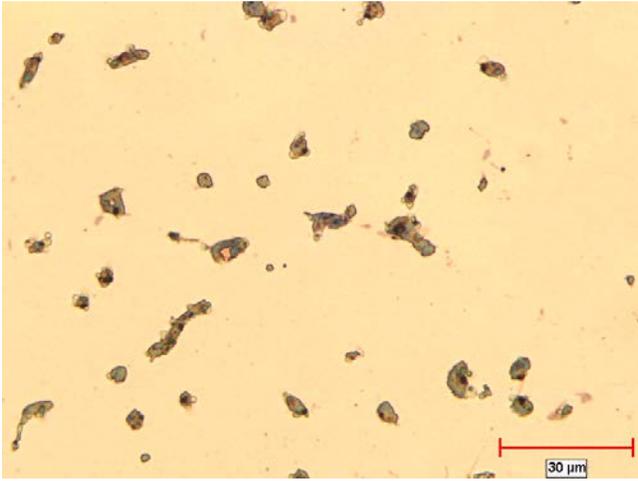
c) Alloy 13, Aged at 300°C for 6 hrs



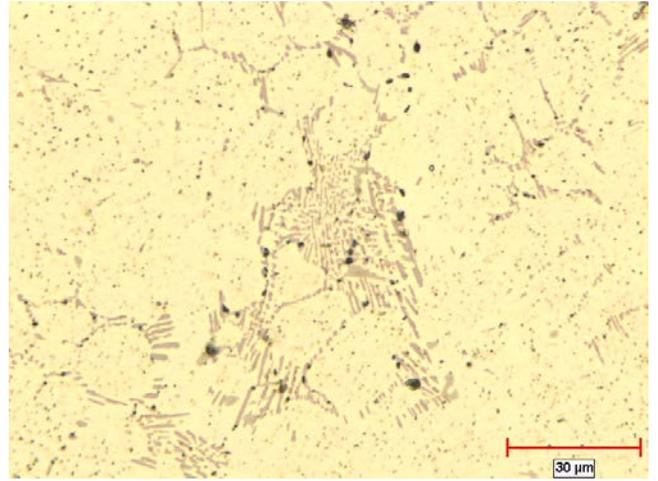
d) Alloy 15, Aged at 300°C for 6 hrs

Figure 5 – Micrographs of heat treated samples.

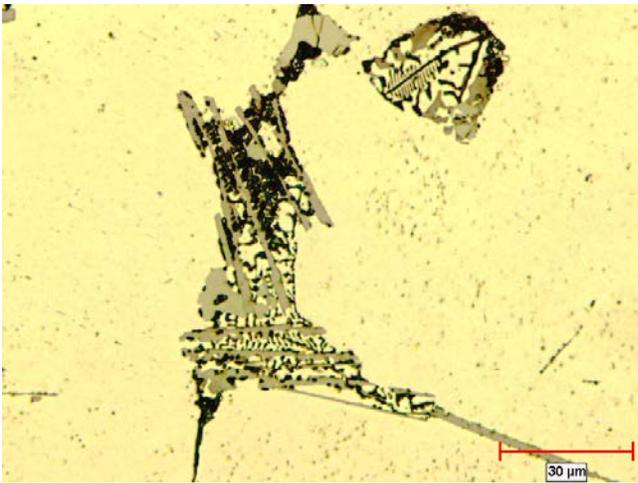
Unetched; 50X magnification



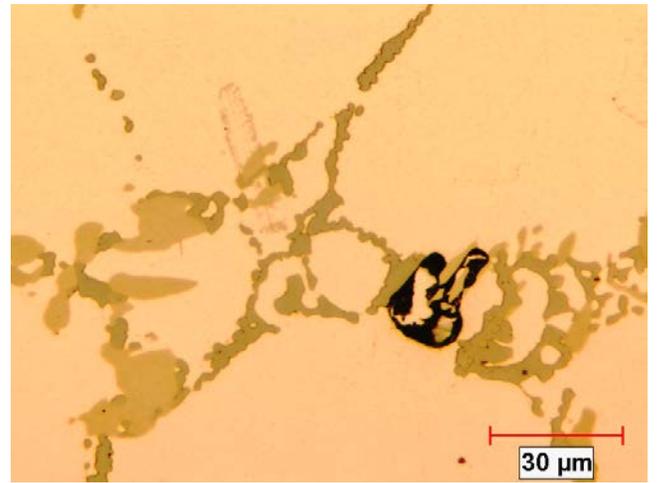
a) Alloy 1, Aged at 210°C for 6 hrs



b) Alloy 10, Aged at 300°C for 10 hrs



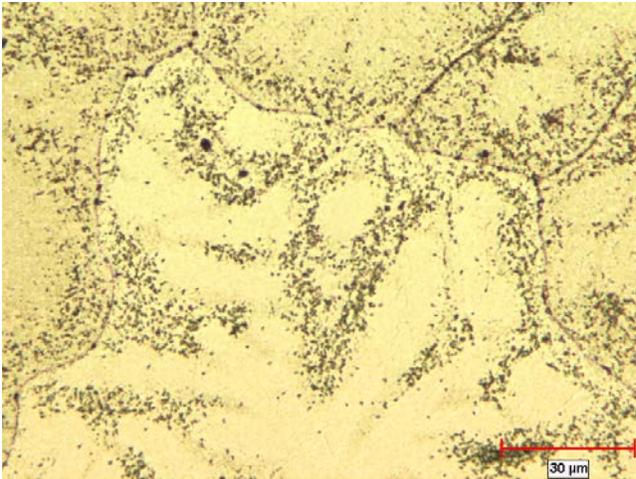
c) Alloy 13, Aged at 300°C for 6 hrs



d) Alloy 15, Aged at 300°C for 6 hrs

Figure 6 – Micrographs of heat treated samples.

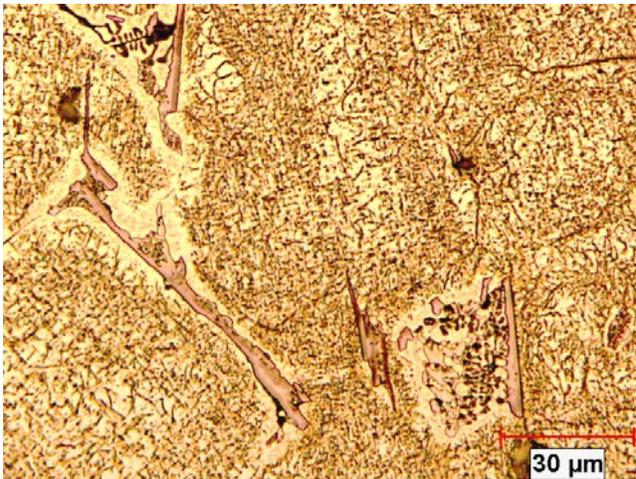
Unetched, 500X magnification



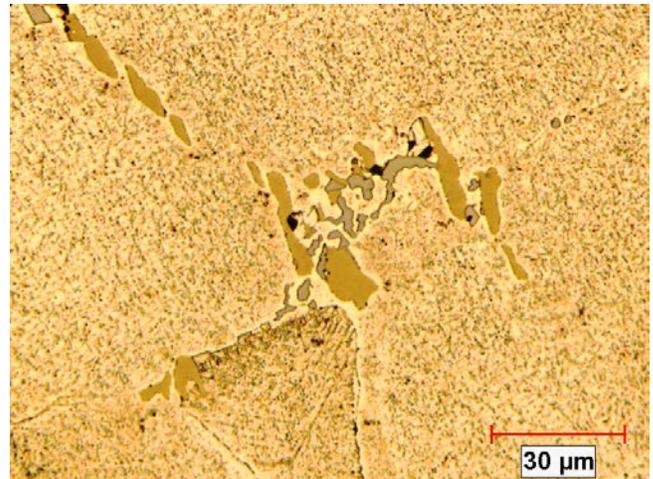
a) Alloy 1, Aged at 210°C for 6 hrs



b) Alloy 10, Aged at 300°C for 10 hrs



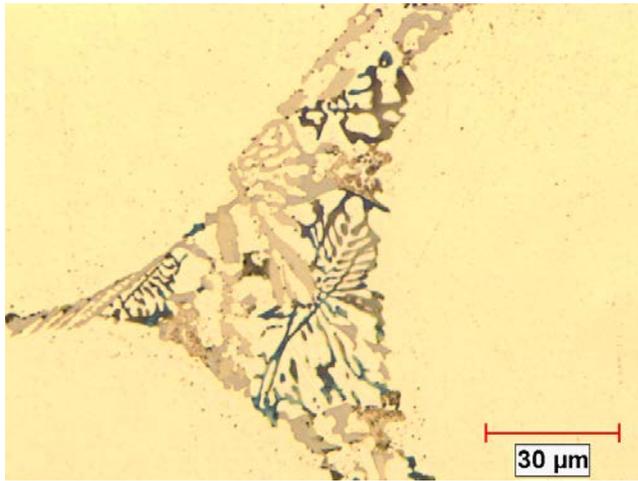
c) Alloy 13, Aged at 300°C for 6 hrs



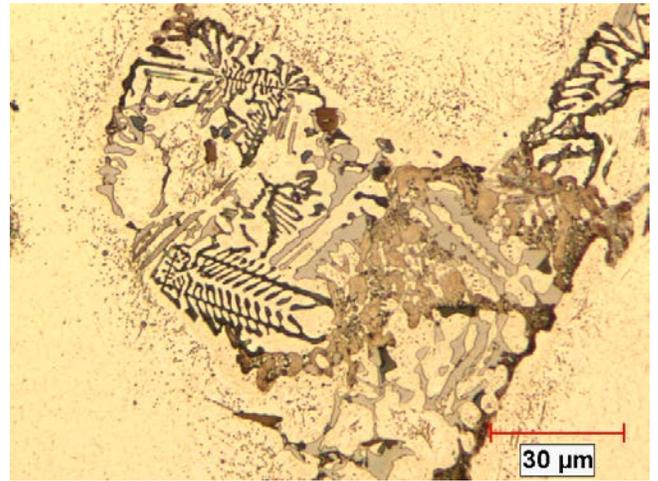
d) Alloy 15, Aged at 300°C for 6 hrs

Figure 7 – Micrographs of heat treated alloys.

Etched; 500X magnification

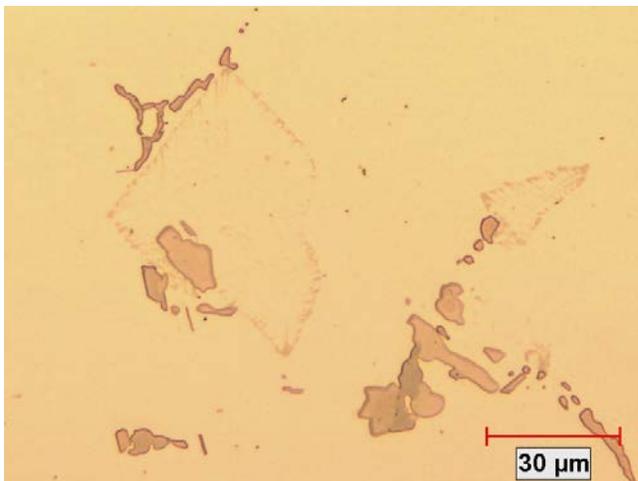


a .Unetched

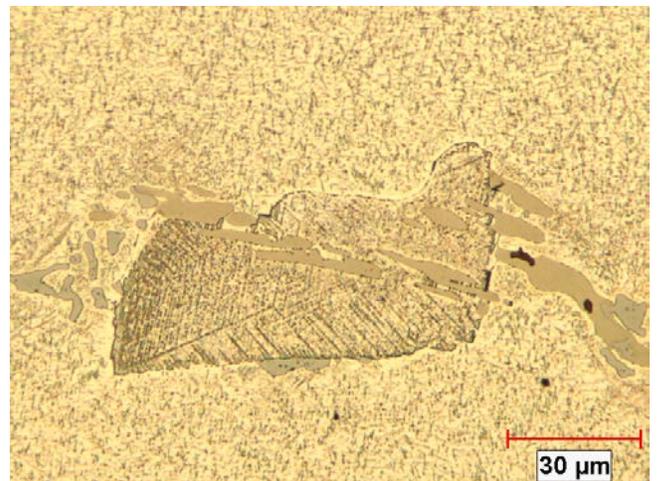


b. Etched, 500 x

Figure 8 - Micrographs of heat treated alloy 13A. Solution heat treated at 590°C for 4 hours followed by ageing at 300°C for 6 hours.

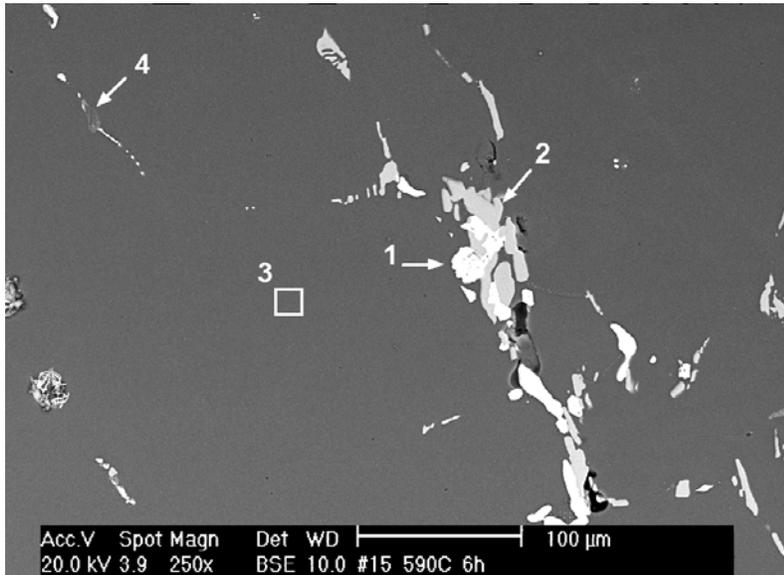


a. Unetched, 500 X

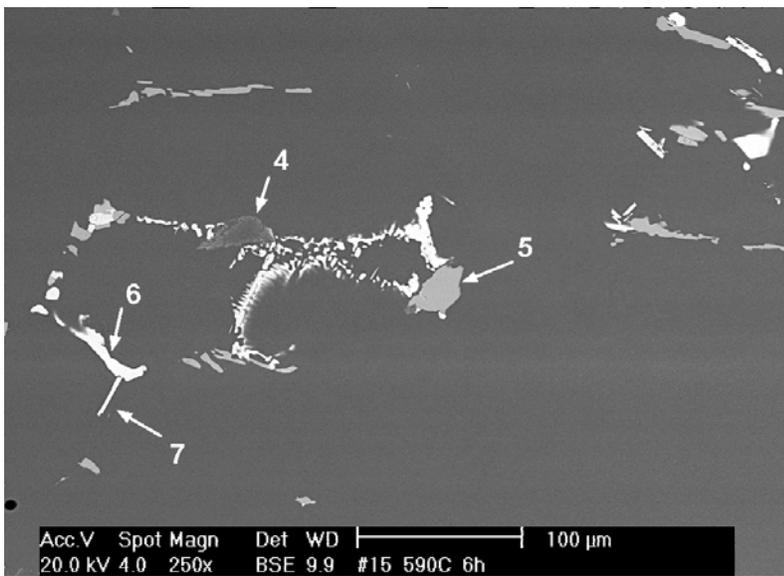


b. Etched, 500 X

Figure 9 - Micrographs of heat treated alloy 15A. Solution heat treated at 590°C for 4 hours followed by ageing at 300°C for 6 hrs



a

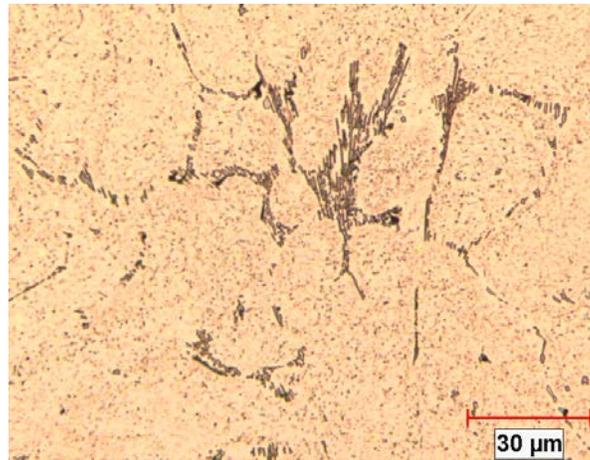


b

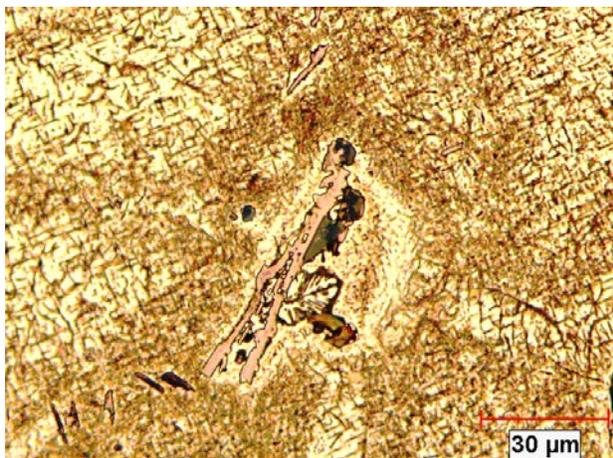
Figure 10 - SEM images showing phases in alloy 15A selected for EDS analysis.

Table 5. Phase constituents in the metallographic specimen of heat treated alloy 15A (see Figure 10 for location and shape of phases).

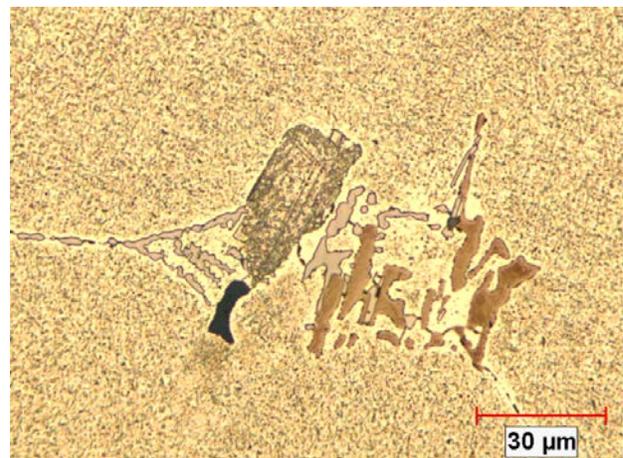
Phase	Al	Cu	Mg	Si	Ni	Mn	Sc	Fe
1	x	x		x	x		x	
2	x	x			x	x		x
3	x	x						
4	x	x					x	
5	x	x			x	x		x
6	x	x			x			
7	x	x		x	x		x	



Alloy 10



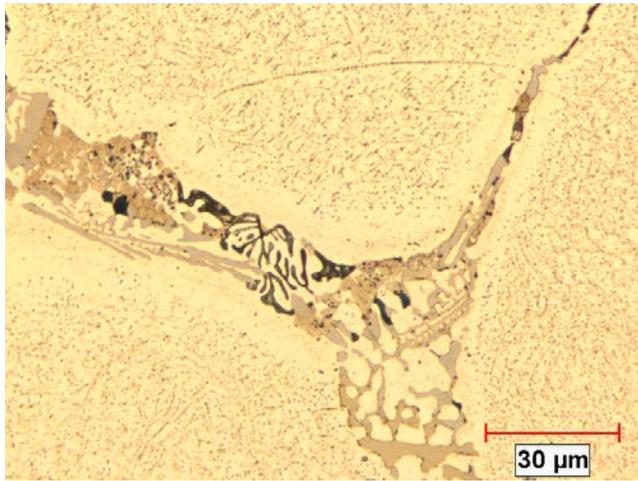
Alloy 13



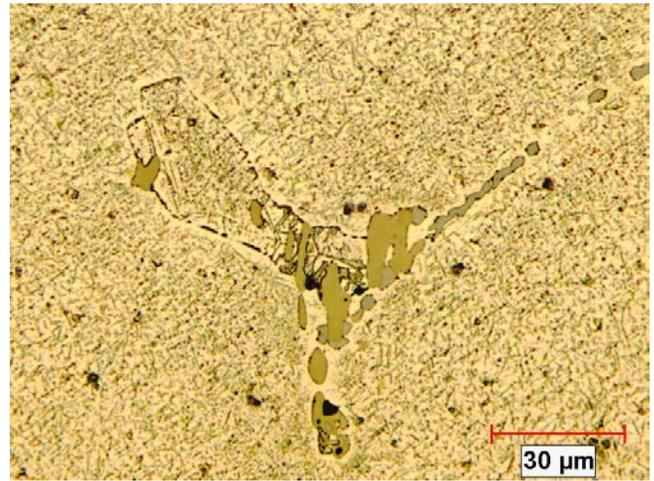
Alloy 15

Figure 11 - Microstructure of samples exposed for 1000 hours at 250°C.

Etched; 500X magnification



a) Alloy 13A



b) Alloy 15 A

Figure 12 – Micrographs of samples exposed for 1000 hours at 250°C, etched, 500X

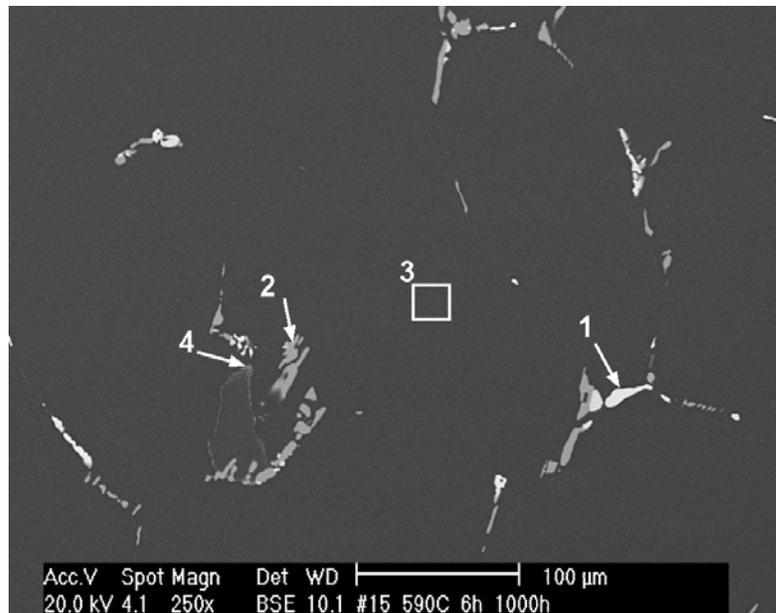


Figure 13 - SEM image showing precipitates in sample 15A exposed for 1000 hr at 250°C

Table 6- Phase constituents in the metallographic specimen #15A exposed for 1000 hr at 250°C (see Figure 13 for location and shape of phases).

Phase	Al	Cu	Mg	Si	Ni	Mn	Sc	Fe
1	x	x			x			
2	x	x			x	x		x
3	x	x	X					
4	x	x	X				x	

*APPENDIX B - Proposed SAE AMS Specification for
AlCuSc Matrix Alloy*

AEROSPACE MATERIAL SPECIFICATION

SAE AMS xxxx

Aluminum Alloy Castings – Elevated Temperature Service
Al2Cu1Mg0.2Sc-T6X
Solution Heat Treated and Artificially Aged

1. SCOPE:

1.1 Form: This specification covers an elevated temperature capable aluminum alloy in the form of castings.

1.2 Application: This aluminum alloy and the castings produced from it are designed for elevated temperature (250°C) service.

2. APPLICABLE DOCUMENTS: The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless specific document issue is specified. When the referenced document has been canceled and no superseding document has been specified, the last published issue of that document shall apply.

2.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001 or www.sae.org.

2.1.1 Aerospace Material Specifications:

AMS 2175	Classification and Inspection of Castings
AMS 2350	Standards and Test Methods
AMS 2360	Room Temperature Tensile Properties of Castings

AMS 2635	Radiographic Inspection
AMS 2645	Fluorescent Penetrant Inspection
AMS 2646	Contrast Dye Penetrant Inspection
AMS 2804	Identification, Castings

2.2 ASTM Publications: Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 or www.astm.org.

ASTM B 557	Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products
ASTM B 557M	Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products (Metric)
ASTM E 29	Using Significant Digits in Test Data to Determine Conformance with Specifications
ASTM E 34	Chemical Analysis of Aluminum and Aluminum Alloys
ASTM E 155	Reference Radiographs for Inspection of Aluminum and Magnesium Castings
ASTM E 227	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Point-to-Plane Technique
ASTM E607	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Point-to-point Technique, Nitrogen Atmosphere
ASTM E716	Sampling Aluminum and Aluminum Alloys for Spectrochemical Analysis
ASTM E1251	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Argon Atmosphere, Point-to-Plane, Unipolar Self-initiating Capacitor Discharge
ASTM E1417	Liquid Penetrant Examination
ASTM E1742	Radiographic Examination

2.3 Aluminum Association Publications: Available from the Aluminum Association, Inc., 900 10th Street, N.W., Washington, DC 20006 or www.aluminum.org.

AA-CS-E18	Cast Surface Smoothness
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3. **TECHNICAL REQUIREMENTS:**

3.1 Composition: Shall conform to the percentages by weight shown in Table 1, determined by wet chemical methods in accordance with ASTM E34, by spectrochemical methods in accordance with ASTM E 227, ASTM E 607, ASTM E 1251, or by other analytical methods acceptable to purchaser (see 3.4.1),

TABLE 1 - Composition

Element	Minimum	maximum
Copper	1.90	2.20
Scandium	0.200	0.260
Magnesium	0.90	1.10
Silicon	0.40	0.60
Nickel	0.45	0.55
Manganese	0.45	0.55
Lead		0.05
Iron		0.08
Other Elements, each (See 8.4)		0.05
Other elements, other		0.15
Aluminum	remainder	

3.1.1 Test results, except for Scandium, may be rounded by the “rounding off” method of ASTM E 29.

3.2 Condition: Solution heat treated and artificially aged.

3.3 Casting: Castings shall be produced in lots from metal conforming to 3.1. Metal remelted from previously analyzed ingot may be poured directly into castings. Furnace or ladle additions of grain refining elements or alloys are permissible. Unless otherwise agreed upon by purchaser and vendor, molten metal taken from alloying furnaces, with or without additions of clean foundry operating scrap (gates, sprues, risers and rejected castings), shall not be poured into castings unless first converted to ingot, analyzed, and remelted or unless the composition of a sample taken after the last addition to the melt has been found to conform to 3.1. The type of mold for casting is not restricted.

3.3.1 A melt shall be the metal withdrawn from a batch-furnace charge of 2000 lb. (900 kg.) or less as melted for pouring castings or when permitted by purchaser, a melt shall be 4000 lb (1800 kg) or less of metal withdrawn from one continuous furnace in not more than 8

consecutive hours.

3.3.2 A lot shall be all castings poured from a single melt in not more than 8 consecutive hours and solution treated in the same heat treatment batch.

3.4 Cast Test Specimens: Chemical analysis specimens, and tensile test specimens when required, shall be cast as follows:

3.4.1 Chemical Analysis Specimens: Shall be cast from each melt and shall be of a size and shape agreed upon by purchaser and vendor.

3.4.2 Tensile Test Specimens: Shall be cast with each lot of castings, shall be of standard proportions conforming to ASTM B557 with 0.500 inch (12.50 mm) diameter at the reduced parallel gage section and shall be cast to size in molds representative of the practice used for castings. Metal for the tensile specimens shall be part of the melt which is used for the castings and poured at the same time as the production castings. The temperature of the metal during pouring of the specimens shall be not lower than that during the pouring of the castings.

3.5 Heat Treatment: The relatively high Cu content of this alloy necessitates a slow increase in the solution heat treatment temperature to prevent liquation of Cu rich areas in the solidified castings. The recommended solution heat treatment and aging temperatures are given below. At the completion of the solution heat treatment, the castings should be rapidly quenched into $154 \pm 10^{\circ}\text{F}$ ($68 \pm 6^{\circ}\text{C}$) water.

Operation	Temperature, °F (°C)	Time @ Temperature, hrs
Solution Heat Treatment	920 (493)	1
	950 (510)	1
	990 (532)	1
	1040 (560)	1
	1090 (588)	1

Warm Water Quench	154 (68)	--
Age (growth of Al ₃ Sc particles)	572 (300)	6

3.6 Properties: Castings and representative tensile test specimens produced in accordance with 3.4.2 shall conform to the following requirements.

3.6.1 Tensile Properties: Shall be as follows, determined in accordance with the ASTM B557; conformance to the requirements of 3.6.1 shall be used as basis for acceptance of castings except then purchaser specified that the requirements of 3.6.1.2 apply.

3.6.1.1 Specimens Cut From Castings: When room temperature tensile properties of actual castings are determined for acceptance, the average of not less than 4, and preferably 10, specimens cut from thick and thin sections of the casting shall be as follows:

3.6.1.1.1 Designated Casting Areas:

Tensile Strength, min.	psi (MPa)
Yield strength at 0.2% offset, min	psi (MPa)
Elongation in 4D, min	%

3.6.1.1.2 Casting Areas Other Than Designated Areas:

Tensile Strength, min.	psi (MPa)
Yield strength at 0.2% offset, min	psi (MPa)
Elongation in 4D, min	%

3.6.1.1.2 When properties other than those of 3.6.1.1.1 or 3.6.1.1.2 are required, tensile specimens as in 4.3.3 taken in locations indicated on the drawing, from a casting chosen at random to represent the lot, shall have the properties indicated on the drawing for such specimens. Property requirements for such specimens may be designated in accordance with AMS 2360.

3.6.1.2 Separately – Cast Test Specimens:

Tensile Strength, min.	psi (MPa)
------------------------	------------

Yield strength at 0.2% offset, min
Elongation in 4D, min

psi (MPa)
%

3.7 Quality:

3.7.1 Castings, as received by purchaser, shall be uniform in quality and condition, sound and free from foreign materials and from internal and external imperfections detrimental to usage of the castings.

3.7.1.1 Castings shall have smooth surfaces and shall be well cleaned. Cast Surface Smoothness may be specified by use of AA-CS-E18.

3.7.2 Castings shall be produced under radiographic control, unless otherwise specified. This control shall consist of radiographic examination of castings in accordance with AMS 2635 until proper foundry technique, which will produce castings free from harmful internal imperfections, is established for each part number and of production castings as necessary to ensure maintenance of satisfactory quality.

3.7.3 When specified, castings shall be subjected to fluorescent penetrant inspection in accordance with AMS 2645 and/or contrast dye penetrant inspection in accordance with AMS 2646.

3.7.4 Radiographic, fluorescent penetrant, contrast dye penetrant and other quality standards shall be as agreed upon by purchaser and vendor. ASTM E155 may be used to define radiographic acceptance standards.

3.7.5 Castings shall not be repaired by peening, plugging, welding or other methods without written permission from purchaser.

3.7.5.1 When permitted in writing by purchaser, defects in castings may be removed and the castings repaired by welding in accordance with AMS 2694.

3.7.6 Castings shall not be impregnated, chemically treated, or coated to prevent leakage unless specified or allowed by written permission of purchaser, designating the method to be used.

4. QUALITY ASSURANCE PROVISIONS:

4.1 Responsibility for Inspection: The vendor of castings shall supply all samples for vendor's tests and shall be responsible for performing all required tests. Results of such tests shall be reported to the purchaser as required by 4.5. Purchaser reserves the right to sample and to perform such confirmatory testing as he deems necessary to ensure that the castings conform to the requirements of this specification.

4.2 Classification of Tests

4.2.1 Acceptance Tests: Tests to determine conformance to requirements for composition (3.1), tensile properties of specimens cut from castings (3.6.1.1) or, when specified, tensile properties of separately cast specimens (3.6.1.2), and quality (3.7) are classified as acceptance tests and shall be performed to represent each lot.

4.2.2 Preproduction Tests: Tests to determine conformance to all technical requirements of this specification are classified as preproduction tests and shall be performed on the first-article shipment of a casting to a purchaser, when a change in material or processing requires re-approval as in 4.4.2, and when purchaser deems confirmatory testing to be required.

4.2.3.1 For direct U.S. Military procurement, substantiating test data and, when requested, pre-production test material shall be submitted to the cognizant agency as directed by the procuring activity, the contracting officer, or the request of procurement.

4.3 Sampling: Shall be in accordance with the following:

4.3.1 Two chemical analysis specimens in accordance with 3.4.1 from each melt or a casting from each lot.

4.3.2 Two pre-production castings in accordance with 4.4.1 of each part number.

4.3.3 Not less than four tensile test specimens machined from castings from each lot except when purchaser specifies use of separately-cast specimens. Specimens shall conform to ASTM B557 and shall be either 0.500 in (12.50 mm) diameter at the reduced parallel gage section, sub-size specimens proportional to the standard, or standard sheet-type specimens. If specimen locations are not shown on the drawing, not less than four specimens, two from the thickest section and two from the thinnest section, shall be cut from a casting or castings from each lot.

4.3.4 Three tensile test specimens in accordance with 3.4.2 from each lot, when purchaser specifies use of separately-cast specimens

4.4 Approval:

4.4.1 Sample castings from new or reworked patterns or molds and the casting procedure shall be approved by purchaser before castings for production use are supplied, unless such approval is waived.

4.4.2 Vendor shall establish for production of sample castings of each part number parameters for the control factors of processing which will produce acceptable castings; these shall constitute the approved casting procedure and shall be used for production castings. If necessary to make any change in parameters for the control factors of processing, vendor shall submit for re-approval a statement of the proposed changes in processing and, when requested, sample castings, test specimens, or both. Production castings incorporating the revised operations shall not be shipped prior to receipt of re-approval.

4.4.2.1 Control factors for producing castings include, but are not limited to, the following:

Type of furnaces

Furnace atmosphere

Mold material

Gating, risering and chilling practice

Fluxing or oxide removal procedures

Pouring temperature (variation of $\pm 50^{\circ}\text{F}$ ($\pm 30^{\circ}\text{C}$) from the established limit is permissible)

Solidification and cooling procedures

Cleaning operations
Solution heat treatment cycle
Heat treat furnace atmosphere
Methods of routing inspection

4.4.2.1.1 Parameters for any of the above control factors of processing considered proprietary by the vendor may be assigned a code designator. Each variation in such parameters shall be assigned a modified code designation.

4.5 Reports:

4.5.1 The vendor of castings shall furnish with each shipment three copies of a report showing the results of tests for chemical composition of at least one casting or of a separately-cast specimen from each melt and the results of tests for tensile properties of specimens cut from castings from each lot or of separately-cast test specimens representing each lot. This report shall include the purchase order number, lot number, AFS 4236, part number, and quantity.

4.5.2 The vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, AMS 4236, contractor or other direct supplier of castings, part number, and quantity. When castings for making parts are produced or purchased by the parts vendor, that vendor shall inspect each lot of castings to determine conformance to the requirements of this specification, and shall include in the report a statement that the castings conform or shall include copies of laboratory reports showing the results of tests to determine conformance.

4.6 Resampling and Retesting: If any specimen used in the above tests fails to meet the specified requirements, disposition of the castings may be based on the results of testing two additional specimens for each original nonconforming specimen. Failure of any retest specimens to meet the specified requirements shall be cause for rejection of the casting represented and no additional testing shall be permitted. Results of all tests shall be reported.

*APPENDIX C - Proposed SAE AMS Specification for
AlCuSc MMC Alloy*

AEROSPACE MATERIAL SPECIFICATION

SAE AMS xxxx

Aluminum Metal Matrix Alloy Castings – Elevated Temperature Service
Aluminum Oxide Particulate (Discontinuous) Reinforced
Al₂Cu1Mg0.2Sc – 10 v/o Al₂O_{3p} - T6X
Solution Heat Treated and Artificially Aged

1. SCOPE:

1.1 Form: This specification covers an elevated temperature capable aluminum metal matrix composite (MMC) alloy in the form of castings.

1.2 Application: This aluminum MMC alloy and the castings produced from it are designed for elevated temperature (250°C) service.

2. APPLICABLE DOCUMENTS: The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless specific document issue is specified. When the referenced document has been canceled and no superseding document has been specified, the last published issue of that document shall apply.

2.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001 or www.sae.org.

2.1.1 Aerospace Material Specifications:

AMS 2175	Classification and Inspection of Castings
AMS 2350	Standards and Test Methods
AMS 2360	Room Temperature Tensile Properties of Castings
AMS 2635	Radiographic Inspection
AMS 2645	Fluorescent Penetrant Inspection
AMS 2646	Contrast Dye Penetrant Inspection
AMS 2804	Identification, Castings

2.2 ASTM Publications: Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 or www.astm.org.

ASTM B 557	Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products
ASTM B 557M	Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products (Metric)
ASTM E 29	Using Significant Digits in Test Data to Determine Conformance with Specifications
ASTM E 34	Chemical Analysis of Aluminum and Aluminum Alloys
ASTM E 155	Reference Radiographs for Inspection of Aluminum and Magnesium Castings
ASTM E 227	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Point-to-Plane Technique
ASTM E607	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Point-to-point Technique, Nitrogen Atmosphere
ASTM E716	Sampling Aluminum and Aluminum Alloys for Spectrochemical Analysis
ASTM E1251	Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Argon Atmosphere, Point-to-Plane, Unipolar Self-initiating Capacitor Discharge
ASTM E1417	Liquid Penetrant Examination
ASTM E1742	Radiographic Examination
ASTM D3553	Standard Test Method for Determination of Fiber Content by Metal Digestion in reinforced Metal Matrix Composites

2.3 Aluminum Association Publications: Available from the Aluminum Association, Inc., 900 10th Street, N.W., Washington, DC 20006 or www.aluminum.org.

AA-CS-E18 Cast Surface Smoothness

2.4 American National Standards Publications: Available from American National Standards Institute

ANSI B74.10 Grading of Abrasive Microgrits

ANSI H35.5 Nomenclature System for Aluminum Metal Matrix Composite Materials

3. TECHNICAL REQUIREMENTS:

3.1 Materials:

3.1.1 Matrix Matrix alloy shall conform to the percentages by weight shown in Table 1, determined by wet chemical methods in accordance with ASTM E34, by spectrochemical methods in accordance with ASTM E 227, ASTM E 607, ASTM E 1251, or by other analytical methods acceptable to purchaser (see 3.4.1),

TABLE 1 - Composition

Element	Minimum	maximum
Copper	1.90	2.20
Scandium	0.200	0.260
Magnesium	0.90	1.10
Silicon	0.40	0.60
Nickel	0.45	0.55
Manganese	0.45	0.55
Lead		0.05
Iron		0.08
Other Elements, each (See 8.4)		0.05
Other elements, other		0.15

Aluminum	remainder	
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3.1.1.1 Test results, except for Scandium, may be rounded by the “rounding off” method of ASTM E29.

3.1.2 Particulate The size of the aluminum oxide particles shall be between 2 and 14 microns; mean size (d_{50}) shall be 6.5 ± 1.0 microns. The concentration of particles in the cast product shall be between 8 and 12 percent by volume.

3.2 Condition: Solution heat treated and artificially aged.

3.3 Casting: Castings shall be produced in lots from metal conforming to 3.1.1. Metal remelted from previously analyzed ingot may be poured directly into castings. Furnace or ladle additions of grain refining elements or alloys are permissible. Unless otherwise agreed upon by purchaser and vendor, molten metal taken from alloying furnaces, with or without additions of clean foundry operating scrap (gates, sprues, risers and rejected castings), shall not be poured into castings unless first converted to ingot, analyzed, and remelted or unless the composition of a sample taken after the last addition to the melt has been found to conform to 3.1. The type of mold for casting is not restricted.

3.3.1 A melt shall be the metal withdrawn from a batch-furnace charge of 2000 lb. (900 kg.) or less as melted for pouring castings or when permitted by purchaser, a melt shall be 4000 lb (1800 kg) or less of metal withdrawn from one continuous furnace in not more than 8 consecutive hours.

3.3.2 A lot shall be all castings poured from a single melt in not more than 8 consecutive hours and solution treated in the same heat treatment batch.

3.4 Cast Test Specimens: Chemical analysis and reinforcement content specimens, and tensile test specimens when required, shall be cast as follows:

3.4.1 Chemical Analysis Specimens: Shall be cast from each melt and shall be of a size and shape agreed upon by purchaser and vendor.

3.4.2 Reinforcement Content Specimens: Shall be cast from the beginning and end of each melt and shall be of a size and shape agreed upon by purchaser and vendor.

3.4.2 Tensile Test Specimens: Shall be cast with each lot of castings, shall be of standard proportions conforming to ASTM B557 with 0.500 inch (12.50 mm) diameter at the reduced parallel gage section and shall be cast to size in molds representative of the practice used for castings. Metal for the tensile specimens shall be part of the melt which is used for the castings and poured at the same time as the production castings. The temperature of the metal during pouring of the specimens shall be not lower than that during the pouring of the castings.

3.5 Heat Treatment: The relatively high Cu content of this alloy necessitates a slow increase in the solution heat treatment temperature to prevent liquation of Cu rich areas in the solidified castings. The recommended solution heat treatment and aging temperatures are given below. At the completion of the solution heat treatment, the castings should be rapidly quenched into $154 \pm 10^{\circ}\text{F}$ ($68 \pm 6^{\circ}\text{C}$) water.

Operation	Temperature, °F (°C)	Time @ Temperature, hrs
Solution Heat Treatment	920 (493)	1
	950 (510)	1
	990 (532)	1
	1040 (560)	1
	1090 (588)	1
Warm Water Quench	154 (68)	--
Age (growth of Al ₃ Sc particles)	572 (300)	6

3.6 Properties: Castings and representative tensile test specimens produced in accordance with 3.4.2 shall conform to the following requirements.

3.6.1 Tensile Properties: Shall be as follows, determined in accordance with the ASTM B557; conformance to the requirements of 3.6.1 shall be used as basis for acceptance of castings except then purchaser specified that the requirements of 3.6.1.2 apply.

3.6.1.1 Specimens Cut From Castings: When room temperature tensile properties of actual castings are determined for acceptance, the average of not less than 4, and preferably 10, specimens cut from thick and thin sections of the casting shall be as follows:

3.6.1.1.1 Designated Casting Areas:

Tensile Strength, min.	psi (MPa)
Yield strength at 0.2% offset, min	psi (MPa)
Elongation in 4D, min	%

3.6.1.1.2 Casting Areas Other Than Designated Areas:

Tensile Strength, min.	psi (MPa)
Yield strength at 0.2% offset, min	psi (MPa)
Elongation in 4D, min	%

3.6.1.1.2. When properties other than those of 3.6.1.1.1 or 3.6.1.1.2 are required, tensile specimens as in 4.3.3 taken in locations indicated on the drawing, from a casting chosen at random to represent the lot, shall have the properties indicated on the drawing for such specimens. Property requirements for such specimens may be designated in accordance with AMS 2360.

3.6.1.2 Separately – Cast Test Specimens:

Tensile Strength, min.	psi (MPa)
Yield strength at 0.2% offset, min	psi (MPa)
Elongation in 4D, min	%

3.6.2 Reinforcement content of two specimens, one each from the beginning and end of each melt shall be tested to confirm that the concentration of particles in the cast product is between 8 and 12 percent by volume.

3.7 Quality:

3.7.1 Castings, as received by purchaser, shall be uniform in quality and condition, sound and free from foreign materials and from internal and external imperfections detrimental to usage of the castings.

3.7.1.1 Castings shall have smooth surfaces and shall be well cleaned. Cast Surface Smoothness may be specified by use of AA-CS-E18.

3.7.2 Castings shall be produced under radiographic control, unless otherwise specified. This control shall consist of radiographic examination of castings in accordance with AMS 2635 until proper foundry technique, which will produce castings free from harmful internal imperfections, is established for each part number and of production castings as necessary to ensure maintenance of satisfactory quality.

3.7.3 When specified, castings shall be subjected to fluorescent penetrant inspection in accordance with AMS 2645 and/or contrast dye penetrant inspection in accordance with AMS 2646.

3.7.4 Radiographic, fluorescent penetrant, contrast dye penetrant and other quality standards shall be as agreed upon by purchaser and vendor. ASTM E155 may be used to define radiographic acceptance standards.

3.7.5 Castings shall not be repaired by peening, plugging, welding or other methods without written permission from purchaser.

3.7.5.1 When permitted in writing by purchaser, defects in castings may be removed and the castings repaired by welding in accordance with AMS 2694.

3.7.6 Castings shall not be impregnated, chemically treated, or coated to prevent leakage unless specified or allowed by written permission of purchaser, designating the method to be used.

4 QUALITY ASSURANCE PROVISIONS:

4.1 Responsibility for Inspection: The vendor of castings shall supply all samples for vendor's tests and shall be responsible for performing all required tests. Results of such tests shall be reported to the purchaser as required by 4.5. Purchaser reserves the right to sample and to perform such confirmatory testing as he deems necessary to ensure that the castings conform to the requirements of this specification.

4.2 Classification of Tests

4.2.1 Acceptance Tests: Tests to determine conformance to requirements for composition (3.1), reinforcement content (3.6.2), tensile properties of specimens cut from castings (3.6.1.1) or, when specified, tensile properties of separately cast specimens (3.6.1.2), and quality (3.7) are classified as acceptance tests and shall be performed to represent each lot.

4.2.2 Preproduction Tests: Tests to determine conformance to all technical requirements of this specification are classified as preproduction tests and shall be performed on the first-article shipment of a casting to a purchaser, when a change in material or processing requires re-approval as in 4.4.2, and when purchaser deems confirmatory testing to be required.

4.2.3.1 For direct U.S. Military procurement, substantiating test data and, when requested, pre-production test material shall be submitted to the cognizant agency as directed by the procuring activity, the contracting officer, or the request of procurement.

4.3 Sampling: Shall be in accordance with the following:

4.3.1. Two chemical analysis specimens in accordance with 3.4.1 from each melt or a casting from each lot.

4.3.2. Two pre-production castings in accordance with 4.4.1 of each part number.

4.3.3 Not less than four tensile test specimens machined from castings from each lot except when purchaser specifies use of separately-cast specimens. Specimens shall conform to ASTM B557 and shall be either 0.500 in (12.50 mm) diameter at the reduced parallel gage section, sub-size specimens proportional to the standard, or standard sheet-type specimens. If specimen locations are not shown on the drawing, not less than four specimens, two from the thickest section and two from the thinnest section, shall be cut from a casting or castings from each lot.

4.3.4 Three tensile test specimens in accordance with 3.4.2 from each lot, when purchaser specifies use of separately-cast specimens

4.4 Approval:

4.4.1 Sample castings from new or reworked patterns or molds and the casting procedure shall be approved by purchaser before castings for production use are supplied, unless such approval is waived.

4.4.2 Vendor shall establish for production of sample castings of each part number parameters for the control factors of processing which will produce acceptable castings; these shall constitute the approved casting procedure and shall be used for production castings. If necessary to make any change in parameters for the control factors of processing, vendor shall submit for re-approval a statement of the proposed changes in processing and, when requested, sample castings, test specimens, or both. Production castings incorporating the revised operations shall not be shipped prior to receipt of re-approval.

4.4.2.1 Control factors for producing castings include, but are not limited to, the following:

- Type of furnaces
- Furnace atmosphere
- Mold material
- Gating, risering and chilling practice
- Fluxing or oxide removal procedures
- Pouring temperature (variation of $\pm 50^{\circ}\text{F}$ ($\pm 30^{\circ}\text{C}$) from the established limit is permissible)
- Solidification and cooling procedures
- Cleaning operations
- Solution heat treatment cycle
- Heat treat furnace atmosphere
- Methods of routing inspection

4.4.2.1.1 Parameters for any of the above control factors of processing considered proprietary by the vendor may be assigned a code designator. Each variation in such parameters shall be assigned a modified code designation.

4.5 Reports:

4.5.1 The vendor of castings shall furnish with each shipment three copies of a report showing the results of tests for chemical composition of at least one casting or of a separately-cast specimen from each melt and the results of tests for tensile properties of specimens cut from castings from each lot or of separately-cast test specimens representing each lot. This report shall include the purchase order number, lot number, AFS 4236, part number, and quantity.

4.5.2 The vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, AMS 4236, contractor or other direct supplier of castings, part number, and quantity. When castings for making parts are produced or purchased by the parts vendor, that vendor shall inspect each lot of castings to determine conformance to the requirements of this specification, and shall include in the report a statement that the castings conform or shall include copies of laboratory reports showing the results of tests to determine conformance.

4.6 Resampling and Retesting: If any specimen used in the above tests fails to meet the specified requirements, disposition of the castings may be based on the results of testing two additional specimens for each original nonconforming specimen. Failure of any retest specimens to meet the specified requirements shall be cause for rejection of the casting represented and no additional testing shall be permitted. Results of all tests shall be reported.