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Process optimisation in the semi-solid forming of hypereutectic Al/Si MMCs

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Abstract
A novel processing route for the fabrication of Al/high silicon MMCs is presented. The silicon size is much finer than can be achieved by casting, yet the materials can still be formed into a near-net shape. Initial properties of the MMCs are presented, and methods under investigation to optimise processing and improve properties are discussed.

Introduction - Hypereutectic Al/Si Alloys
Hypereutectic Al/Si alloys have been used for some years in the automotive industry, and in other fields where wear resistance, high specific stiffness and thermal stability are required (1). Typical uses for hypereutectic Al/Si alloys are: pistons, engine blocks, connecting rods and pump and hydraulic components. Such components are usually made using conventional casting techniques, or by DC casting, hot working and machining (2).

The most commonly used alloy is the 390 series (3), which contains 16-18 wt.% silicon, as well as 5% copper and 0.5% magnesium. This alloy possesses a higher wear resistance than most aluminium alloys, and 10-15% greater specific stiffness, along with ~15% lower coefficient of thermal expansion. Although such improved properties are significant, increased silicon loading holds out the promise of even greater improvements, moving into the realm of a true composite, if certain processing difficulties can be overcome.

Hypereutectic Al/Si alloys possess two advantages compared to other Al-MMCs:
- the particulate phase is formed in situ from the melt, so there is no reaction at the Al/Si interface and particulate-matrix bonding is very strong
- forming from the melt also means that the MMCs can readily be recycled, or used as components in alloys lower in silicon. This will have a significant effect on the cost of the alloys, as refining Al consumes 20 times as much energy as remelting it (4)

The source of the processing difficulties is the steep liquidus in the hypereutectic region of the Al/Si phase system. The solidification range of the alloys rises rapidly with silicon content, with the consequence that the primary silicon phase soon becomes coarse, even when phosphorus refinement during casting is used. Refinement has been shown in the present study to have an appreciable effect on silicon size and morphology at Si contents up to 36wt. %, reducing the maximum particle size achieved at moderate cooling rates from 300μm to 100μm. However,
this is still too large, and properties such as strength, toughness and ductility are compromised. In addition, at these high Si contents, it is necessary to perform the melting and refinement under an inert atmosphere. This itself is a consequence of the high melt temperatures necessary for casting in the hypereutectic region, as it appears that the aluminium phosphide nucleant oxidises at temperatures in excess of 750°C. (Al/36Si was cast into a copper wedge mould at 900°C).

The silicon content of the 390 series of alloys corresponds to the maximum casting fluidity. It has been found that the wear resistance of cast hypereutectic Al/Si alloys is not improved significantly by Si loadings above 16-18% (3), so it is reasonable to choose a composition which facilitates processing. This is especially the case when hypereutectic Al/Si alloys are found to possess rather poor shrinkage feeding characteristics, requiring high melt superheat and mould temperature gradients and complex multiple gating systems in order to promote directional solidification and a uniform Si distribution (3,5).

The steep liquidus in hypereutectic Al/Si alloys also means that practical problems become greater at higher Si contents. Thus, in order to achieve a loading of 25% Si, a melt temperature of ~800°C is required, with the attendant difficulties of wear of dies and refractory components, oxidation and gas pick-up in the melt (5,6).

**Spray-forming and Thixoforming Hypereutectic Al/Si MMCs**

The approach of the present project (which is a BRITE/EURAM collaboration, involving six Partners, from Spain, Britain and Germany), is to try to circumvent some of the problems encountered with casting hypereutectic Al/Si alloys, and thus to achieve higher silicon loadings, while maintaining a fine silicon particle size. This can only be done by using a rapid solidification technique. In summary, the route chosen was as follows:

- Production of preforms using the Osprey process (7), in which the melt is atomised in an inert gas and collected on a rotating former. The resulting preform possesses a non-dendritic microstructure suitable for semi-solid processing (8). Spray-forming achieves the cooling rates typical of powder metallurgy ($10^4-10^6 \text{K s}^{-1}$), while avoiding some of the processing steps.
- Machining of the preform and extrusion into a round bar. This eliminates any residual porosity from the spray-forming, and in the case of the hypereutectic Al/Si system, breaks up the continuous silicon network (9).
- Near-net shaping of billets machined from preforms or cut from the extruded bar by thixoforming. The billet is heated into the semi-solid region, where, because it is non-dendritic, it behaves in a thixotropic manner. This means that when left undisturbed the billet is solid, but when sheared it flows like a liquid. Thixoforming restricts microstructural coarsening as the processing temperatures and liquid contents are low. Alongside this advantage, which is of particular importance for the hypereutectic Al/Si system, thixoforming offers a number of other benefits. The low temperatures and forming pressures reduce solidification shrinkage and die attrition, and allow the use of die materials which are more easy to machine than tool steel. Laminar flow of the slurry in the die reduces gas and lubricant entrapment, and also particle segregation when composites are thixoformed. Solidification occurs under pressure: when suitable die designs are employed, shrinkage porosity can be eliminated.

**Experimental**

Samples were spray formed in the binary system (Al/Si, with 20-50 wt.% Si) and the ternary Al/25-40Si/5Cu system. The spray-forming operations were performed at Osprey Metals Ltd., Neath, South Wales. Conditions were chosen such as to minimise Si particle size, consistent
with good product yield and minimal porosity. A typical as-sprayed microstructure is shown in Figure 1. The silicon is very fine, with a maximum size of \(\approx 15\) μm, and the microstructure consists solely of Al (which is supersaturated with \(\approx 5\) wt. % Si), and silicon grains which appear to have solidified together. The micrograph also suggests that both the Si and Al phases form continuous networks. This has been confirmed by dissolution of the Al phase (9). The ternary alloys form a similar microstructure, with CuAl2 also present, surrounding the Si grains. The silicon size tends to be somewhat larger (Figure 2).

Thixoforming of 60mm high by 60mm diameter billets was performed in the Sheffield rig (supplied by Servotest Ltd., Twickenham, UK). A schematic diagram of this rig is shown in Figure 3 (overleaf). The system consists of a computer-controlled servohydraulic actuator driving a ram, which is used to force the billet upwards into a die. The billet is placed on the lower ram in the induction heater. The billet condition is monitored by two temperature probes and the heating regime is adjusted to ensure that the temperature difference on thixoforming is \(<5^\circ\text{C}\).

When the sample is ready to thixoform, the lower ram rises at a predetermined velocity, the billet is sheared and the alloy slurry fills the die. When die filling is complete, a pre-set load is applied while solidification takes place.

Several die shapes were used, making rectangular bars of different dimensions for machining into test pieces. The die material was graphite. No special measures were taken to promote directional solidification. Alloys in both the binary and ternary (Al/Si/Cu) systems were thixoformed, along with a reference alloy, with a composition close to A390 (Al/17Si/5Cu/0.5Mg), supplied by the Showa Aluminium Corporation, Oyama, Japan. This alloy had been made by DC casting and therefore possessed a more coarse microstructure than the spray-formed alloys, but was thixoformable because the dendrites had been broken up by extrusion.

A systematic testing programme is still underway, the object being to evaluate different alloy compositions and thixoforming procedures. As the testing is not complete, sample results only will be quoted here, to give some idea of the trends which can be expected and the properties it is hoped to consistently achieve. The testing has been performed by three Partners:

- Lucas Advanced Engineering Centre - wear, corrosion, tensile tests, microstructure, moduli by resonance
- Ruhr-Universität Bochum - thermal expansion, wear, DTA, microstructure
Results and Discussion
a) Binary Al/Si alloys
The alloys Al/20Si, Al/36Si and Al/50Si proved increasingly difficult to thixoform as the silicon content rose (9). Flaws were often present in the products. These could be described as follows:

- **Al/20Si** - segregation between large (>1mm) regions where the metastable $\alpha$-Al phase was present and those where it was not: the liquid content varied considerably through the billet.
- **Al/36Si** - no $\alpha$-Al phase, but some Si segregation and coarsening (Figure 4)
- **Al/50Si** - no $\alpha$-Al phase; silicon macrosegregation and coarsening up to 200µm; cold shuts

These flaws were considered to arise from the fact that the $\alpha$-Al phase disappeared within 2-3 minutes of the alloys reaching the eutectic temperature of 577°C. The Al/Si phase diagram shows that, at equilibrium, these alloys will possess 60-90% liquid at the eutectic temperature. Experience has shown that it takes up to 5 minutes for the centre of a billet to reach the thixoforming temperature, after the outside is already at this point. It is therefore very difficult to maintain a low liquid content in the binary Al/Si system, and even more so to establish a near-uniform liquid content through the billet. If the liquid content was too high, or non-uniform, then turbulent flow would be expected, leading to the kinds of defects mentioned above.

b) The ternary systems Al/28Si/5Cu, Al/34Si/5Cu and Al/40Si/5Cu and the Showa alloy
Following the experience with the binary alloys, it was decided to search for a ternary component which would allow a more gradual rise in liquid content above the solidus. From the Al/Si/Cu phase diagram, it was felt that addition of 5 wt. % copper could have the desired effect (9): because the Al/Si/Cu eutectic contains nearly 30% copper, the melting of an Al/Si/5Cu alloy at the eutectic temperature (525°C) could only produce ~5% of liquid. (At this temperature Al contains up to 2.5% dissolved copper). Between 525°C and ~570°C, solid $\alpha$-Al and Si exist in

![Figure 3: The Sheffield University Thixoforming Press](image)

![Figure 4: Thixoformed Al/36Si: Si + eutectic and Si coarsening](image)
equilibrium with the liquid, both dissolving gradually as the temperature increases providing a range of \(-45^\circ C\) where the liquid content is rising gradually. Copper addition has the further advantage of providing a heat treatable alloy.

Figure 5 illustrates the change of particle size with Si content in the \(\text{Al}/\text{Si}/\text{Cu}\) system after spray-forming and thixoforming, showing the limited particle coarsening which results from control of the liquid content on thixoforming. The behaviour of the DC-cast Showa alloy is similar, even though this material was made under conditions closer to equilibrium. Isothermal tests have shown that with all the alloys there is also a strong time dependence of liquid content, with Al and Si continuing to dissolve for at least 10 minutes when the alloys are held at \(560^\circ C\). Thus the thixoformed microstructures (Figure 6) indicate low liquid contents, even though thixoforming is performed at temperatures close to the top of the range discussed above.

c) Properties of thixoformed ternary alloys

Figure 7 (overleaf) shows the thermal expansion and specific Young's moduli, in comparison with aluminium and steel, showing definite trends in both properties as the Si content increases. These figures illustrate the potential value of MMCs with very high silicon loadings, showing a specific stiffness which well surpasses steel, and a thermal expansion close to it, which is useful in automobile applications (10).

Tensile strength values have been in the range 200-250 MPa in the un-heat treated condition, with fracture strengths up to 487 MPa. This marked difference, along with fractography studies, suggests that the strength is dominated by the presence of flaws, and by the clustering of silicon particles. The thixoformed alloys are still being evaluated for their wear resistance. Some abrasive and pin-on-disc wear tests have been completed, and indicate that all the alloys possess similar wear resistance, irrespective of silicon content. This may be due to the increasing hardness with Si content being offset by the effects of larger Si sizes. Therefore, one objective is to find methods of refining the silicon size further.

Conclusion

The promising results outlined above indicate the potential of the chosen route for the fabrication of Al/high silicon MMCs. Two areas, however, require further study if strong MMCs which are consistently defect-free are to be produced:
Altering the design and materials of the thixoforming die so that processing flaws are eliminated. These flaws are cold shuts and shrinkage porosity.

Reducing the silicon size still further in order to raise the strength and to increase the wear resistance.

The first matter is currently under investigation, and centres on adjustment of the rates of heat extraction from the semi-solid slurry as it fills the die and subsequently solidifies.

On the second matter, it has recently been found that small magnesium additions reduce the silicon size in as-sprayed Al/Si/Cu MMCs, and this is carried over into the thixoformed products. The properties of samples with added Mg are currently being determined.

Process optimisation in the spray-forming and thixoforming of hypereutectic Al/Si-based metal matrix composites has required the consideration of both alloy composition and processing conditions, and the interplay between them. The process illustrates the potential this new class of Al-composites. It also illustrates the versatility of the spray-forming and thixoforming techniques, and indicates some paths along which they could be developed, using other alloy or composite systems.

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References

1. TENEKEDJIEV N. & GRUZLESKI J. E., Cast Metals 3 (1990) 95.