SEMI-SOLID PROCESSING OF HYPEREUTECTIC AL/SI ALLOYS

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Abstract

A study of semi-solid processing of spray-formed hypereutectic Al/Si has been undertaken. DTA-measurements have been executed to determine the temperature range suitable for thixoforming. Consequently, heat treatments in the semi-solid state have been carried out to investigate the influence of temperature, dwell time and chemical composition on the remelting behaviour.

Introduction

The drive in the automotive and aerospace industries to reduce weight and energy consumption has stimulated the development of MMC's. Conventional hypereutectic Al/Si alloys are notable for their high wear resistance, reduced thermal expansion coefficient and specific stiffness. However poor ductility resulting from difficulties in controlling the primary Si particle size and morphology and the width of the melting range in the hypereutectic region which causes porosity limits the maximum silicon content in cast Al/Si to approximately 25 w/o.

These difficulties can be overcome by semi-solid processing which relies on the peculiar flow behaviour of slurries containing a suspension of spherical solid particles in a liquid (Fig. 1) /1/. These slurries can be thixotropic that means that the apparent viscosity depends on shear rate and time. Before stirring the viscosity of the slurry is on a high level. A critical shear rate causes a significant decrease of the viscosity to a lower level. On interrupting the shear movement they begin to stiffen and become more viscous.

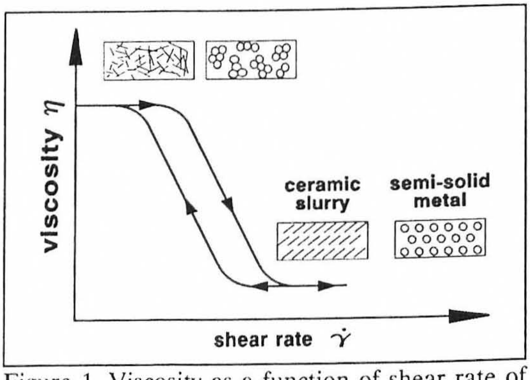


Figure 1. Viscosity as a function of shear rate of thixotropic materials /1/.

This reversible behaviour is well known from ceramics slurries which consist of platelike solids /2/. At standstill the irre-

gular distributed solids support each other resulting in an increased flow resistance. Stirring the slurry leads to an unidirectional orientation of the platelike solids parallel to the flow direction. Furthermore the change of the viscosity depends on the stirring time.
In the last few years this phenomenon has gained in importance for near-net shaping of light metals due to the multitude of benefits. According to a theory of Kumar and Brown the interfacial tension of the solid particles causes agglomerations in the unsheared condition and therefore a high viscosity /3/. The shear movement leads to a significant decrease of the viscosity due to the dissolution of the agglomerations.
The requirement for a suspensions of solid particles in a metallic liquid is a two-phase region with a significant solidification range.
Different processes have been developed to produce suitable raw materials for thixoforming. Mechanical stirring of the liquid during solidification has been effectively abandoned as a commercial route due to the high wear rate of the stirrer and the low productivity. In contrast to mechanical stirring electromagnetic stirring induces fluid flow in the liquid metal without any contact with the stirrer /4/. Because the forces which induce liquid flowing motion act on the whole metal, stirring is much more efficient throughout the mushy zone. Another method involves production of billets by standard DC casting followed by an extrusion step. During the reheating of the material, recrystallisation processes take effect leading to a grain refinement before partial melting. At this state, liquid penetrates grain boundaries and produces a fine non-dendritic microstructure. Spray compaction has been employed successfully to produce thixotropic alloys, but the production costs of this process are higher compared to the methods mentioned above /5/.

Experimentals

Different hypereutectic binary Al/Si and ternary Al/Si/Cu alloys with a silicon content from 20 up to 50 w/o have been produced by spray compaction. In the Osprey process a stream of liquid metal is atomized by an inert gas jet and deposited in the semi-solid state on to a rotating target. Spray forming conditions, such as melt superheat, nozzle diameter, spray distance, gas/metal ratio etc. were adjusted to achieve a minimum silicon particle size while also keeping the porosity in the preform as low as possible.
To investigate the temperature range suitable for semi-solid processing, DTA-measurements have been performed on the sprayformed materials. Based on the results of the DTA-measurements, heat treatments in the semi-solid state have been executed to investigate the remelting behaviour depending on temperature, dwell time and chemical composition. After the heat treatment in the semi-solid state the samples have been quenched in water and prepared for microstructural analysis.

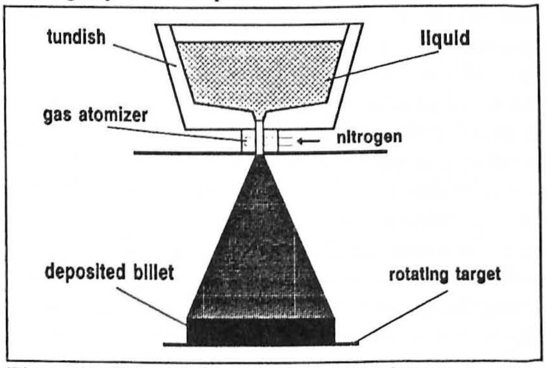


Figure 2. Schematic arrangement of Osprey compaction process /6/.

Results and Discussion

The curves of the DTA-measurements of the binary sprayformed materials show endothermal reactions at a temperature of approximately 580°C which matches the binary eutectic temperature of 577°C of the binary Al/Si phase diagram (Fig. 3).

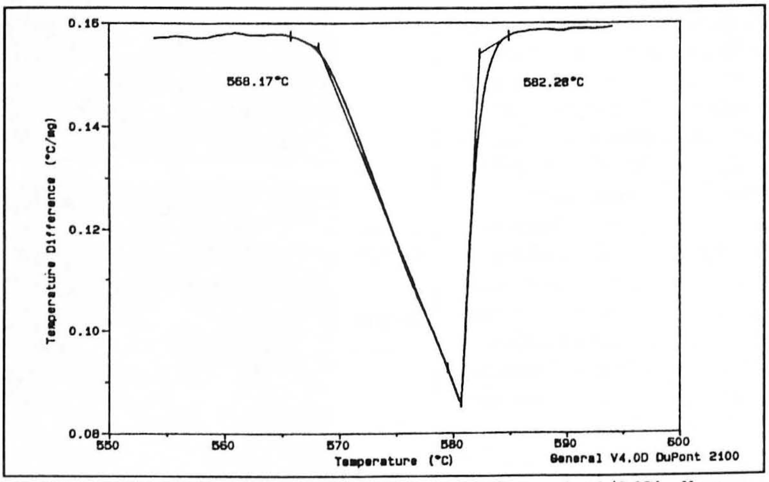


Figure 3. DTA-measurement of the sprayformed Al/36Si alloy.

The addition of 5 w/o Cu leads to a further endothermal reaction at a temperature which is nearly coincident with the ternary eutectic temperature of 524°C (Fig. 4). Furthermore the Cu addition causes a decrease of the binary eutectic temperature.

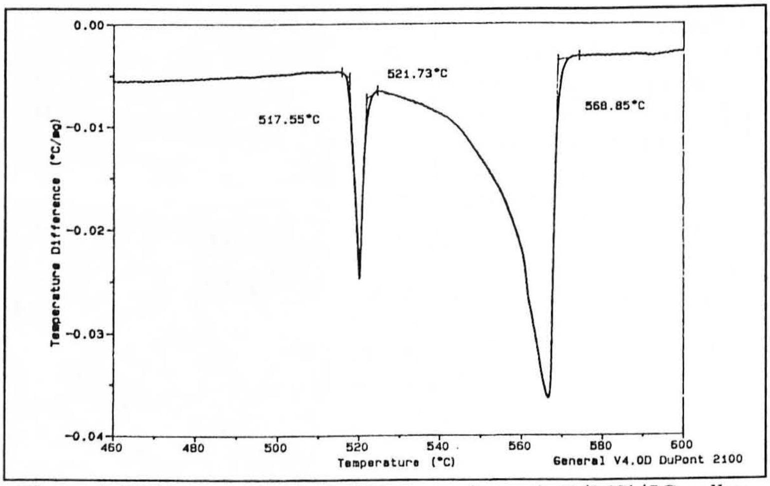
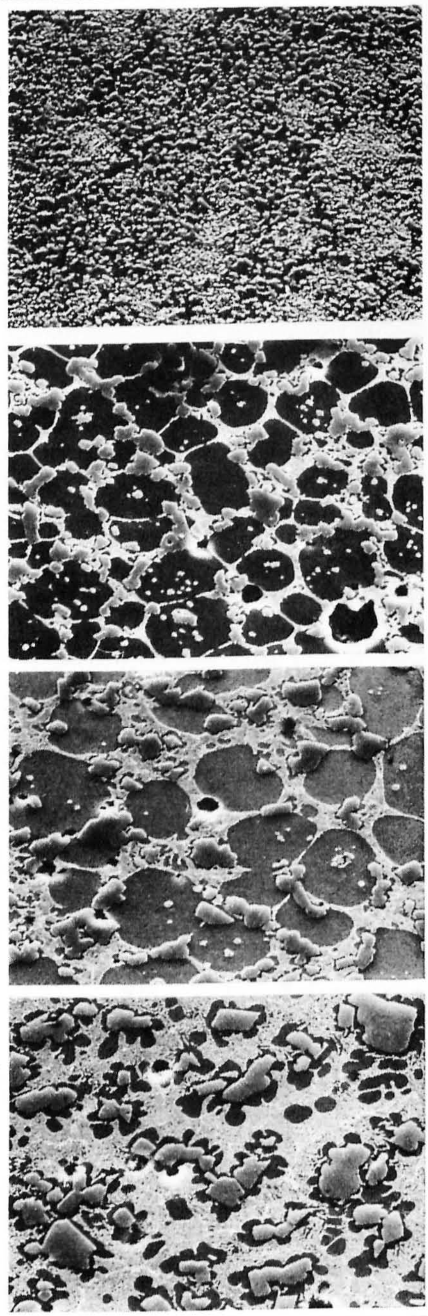


Figure 4. DTA-measurement of the sprayformed Al/36Si/5Cu alloy.

In contrast to conventional cast hypereutectic alloys which consist of large Si primary crystals embedded in an eutectic, the Osprey process was shown to produce a very fine microstructure due to the high cooling rate (Fig. 5a). It consists of homogeniously distributed Si primary particles in an aluminium matrix and is indicative of non-equilibrium solidification as a result of the sprayforming process.

Based on the results of the DTA-measurements, heat treatments at a temperature of 585°C have been carried out on the binary Al/Si alloys. Figures 5b-d show the microstructures after the heat treatment in the semi-solid state in dependence of different dwell times. A dwell time of 4 minutes leads to a microstructure which consists of Si primary crystalls and spherical α-Al particles, embedded in a eutectic matrix which obviously has been liquid during the heat treatment due to the fact that no eutectic is present in the spray-formed condition (Fig. 5b). This suspension of spherical solids in a liquid which seems to be suitable for thixoforming is only metastable. Increasing the dwell time up to 6 minutes causes a higher amount of liquid (Fig. 5c). After a dwell time of 12 minutes the usual equilibrium state is present containing coarsened Si primary particles in an eutectic (Fig. 5d).



a) spray-formed state 20 µm

b) 4 min. 585°C 20 µm

c) 6 min. 585°C 20 µm

d) 12 min. 585°C 20 µm

Figure 5 a-d. Microstructures of the spray-formed Al/20Si after heat treatment in the semi-solid state.

The schematic model of the remelting process of the binary alloys is given in figure 6. The binary Al/Si phase diagram with the temperature of the heat treatment T_1 and the chemical composition c_0 of the alloy is shown in figure 6a.
The degree of concentration in the spray-formed material at the α-Al/Si interface is displayed in figure 6b. The non-equilibrium condition is characterized by a concentration leap c_{Si} to c_α at the interface.
With increasing dwell time at a temperature T_1, diffusion processes cause an eutectic concentration at the α-Al/Si interface which leads to a local remelting (figure 6c). In this state the liquid is on the one hand in a metastable equilibrium with the α-Al and on the other hand with the Si. The concentration gradient $\Delta c = c_{L/Si} - c_{L/\alpha}$ is responsible for the progress of the remelting process.
Due to the fact that the created liquid is of eutectic concentration, the α-Al is much more reduced than the Si. Finally, the equilibrium condition is established which consists of primary Si particles surrounded by a liquid.

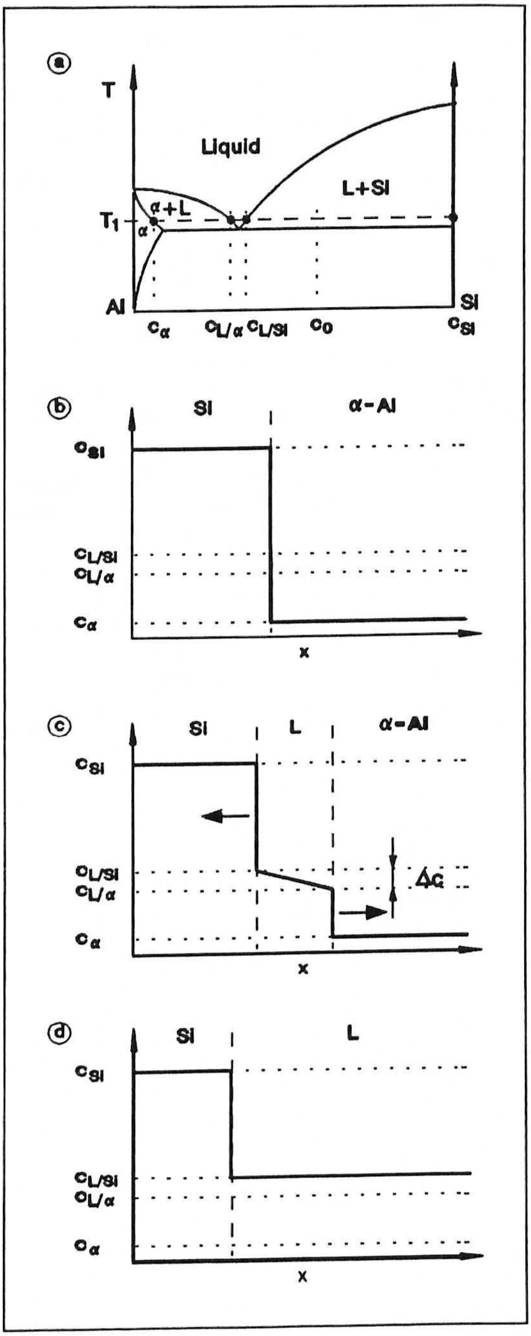


Figure 6 a-d. Schematic model of the remelting process.
a) binary Al/Si phase diagram.
b) degree of Si-concentration at the α-Al/Si interface, non equilibrium state.
c) degree of Si-concentration at the interface α-Al/L/Si, metastable state.
d) degree of Si-concentration at the L/Si-interface, equilibrium state.

Based on the results of the DTA-measurements, further heat treatments have been performed on the spray-formed ternary Al/Si/Cu alloys to investigate the influence of temperature, dwell time and chemical composition on the remelting behaviour.
The microstructure of the sprayformed Al/25Si/5Cu alloy is exemplary presented in figure 7a. It consists of homogenously distributed Si primary particles embedded in an α-Al matrix. Furthermore, fine Al_2Cu particles close to the Si can be observed.
A heat treatment between the binary and ternary eutectic temperature causes a partial remelting of the spray-formed material according to the reaction α-Al + Si + Al_2Cu $\Rightarrow$ Liquid (figure 7b).
Increasing the dwell time in the semi-solid state up to 10 minutes produces a higher amount of liquid (figure 7c). In that period of time an equilibrium is achieved so that after further heat treatment no increase of liquid amount can be observed (figure 7d). The change of microstructure due to longer dwell times is limited to an enlargement of the Si primary particles and the spherical α-Al particles. This condition is especially suitable for semi-solid processing since the suspension consists of spherical α-Al and Si particles which are homogeniously distributed in the liquid.
A further advantage is the possibility of adjusting the liquid/solid ratio with the setting of the temperature.

a) spray-formed state 20 μm

b) 5 min. 560°C 20 μm

c) 10 min. 560°C 20 μm

d) 30 min. 560°C 20 μm

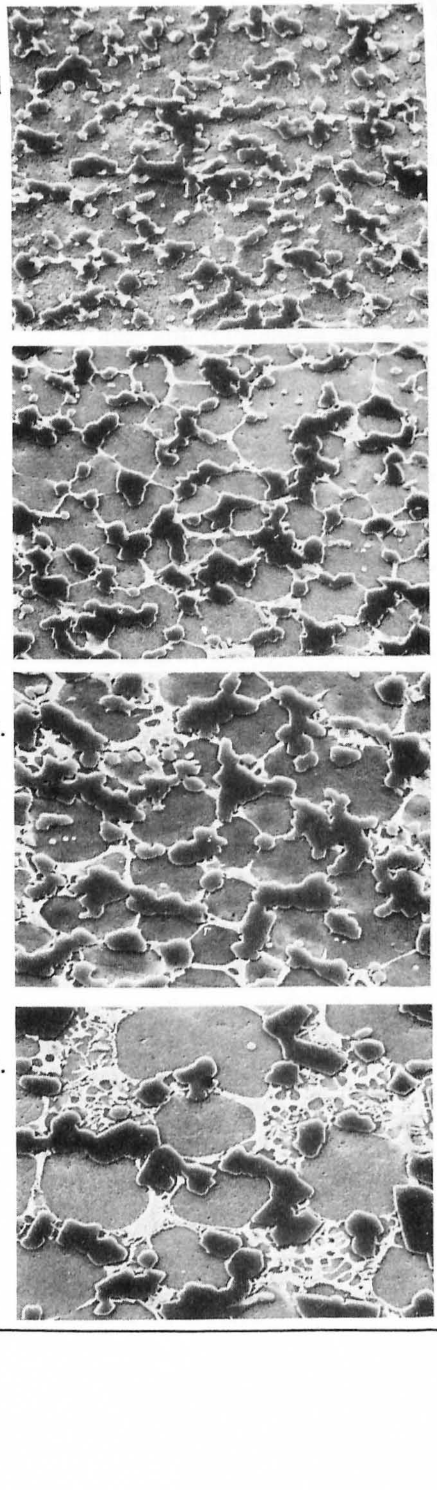


Figure 7 a-d. Microstructures of the spray-formed Al/25Si/5Cu alloy after heat treatment in the semi-solid state.

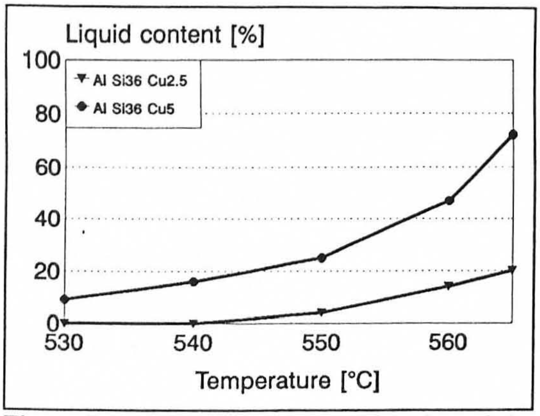


Figure 8. Amount of liquid as a function of the temperature of heat treatment.

Heat treatments have been carried out on ternary Al/Si/Cu alloys for 15 minutes in the range between the ternary and binary eutectic temperature. The amount of liquid as a function of temperature and Cu content is given in figure 8.
The amount of liquid can be adjusted in a wide range for ternary alloys with a Cu content of 5 w/o. Reduced Cu concentrations lead to missing the ternary eutectic reaction so that the necessary liquid ratio for semi-solid processing cannot be adjusted.
Based on the results of these heat treatments hypereutectic Al/Si alloys have been successfully formed to near-net-shape by thixoforming at the University of Sheffield.

Conclusions

In the binary eutectic Al/Si system (20-50 w/o Si), it is difficult to control the liquid contents close to the solidus temperature. The suspension of spherical α-Al and Si particles in a liquid, which is necessary for thixoforming at low liquid contents, is only metastable. The addition of 5 w/o Cu stabilises the α-phase in the spheroidal form and allows the variation of the liquid content in a wide range and therefore improves the thixoformability of hypereutectic alloys.

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References

1. H.-P. Erz, Giesserei 77, (1990), Nr. 19, 613-617.

2. H. Salmang, H. Scholze, Keramik Teil I: Allgemeine Grundlagen und wichtige Eigenschaften, (Berlin, 1982).

3. B. Brown, P. Kumar, Int. Conf. Semi solid processing of alloys and composites, 4.-6. April 1990, Cemef, Sophia Antipolis, France.

4. M. P. Kenny, et al., Metals Handbook, ninth Ed., Vol. 15, 327-338.

5. A. R. A. McLelland, et al., "Thixoforming Spray-Formed Metal Matrix Composites", First Int. Conf. on Spray Forming, Swansee, Wales.

6. R. W. Evans, A. G. Leatham and R. G. Brooks, Powder Metallurgy, Vol. 28, No. 1 (1985), 13-20.