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Hypereutectic Al–Si based alloys with a thixotropic microstructure produced by ultrasonic treatment

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The present investigation attempts to evaluate the effect of an ultrasonic treatment on the microstructure of hypereutectic Al–Si based alloys. In conventional casting solidified at a moderate cooling rate, the primary silicon crystallizes in the form of hexagonal plates joined together at the centre into star-shaped particles, as they appear in cross-section. During the ultrasonic treatment most of the silicon plates were disconnected and broken, forming spheroidized crystals. The ultrasonic treatment results in an increase of the plasticity and strength of the alloys. To study the thixotropic behaviour, ultrasonically treated and non-treated specimens were upset in an electrohydraulic press under semi-solid conditions. The investigation confirms great advantages of ultrasonically treated ingots of Al–Si based alloys upon deformation in the semi-solid state.

Keywords: ultrasonic treatment; hypereutectic aluminium alloys; thixocasting; mechanical properties

Introduction

Spencer *et al.*[1] pioneered a study on the behaviour of metals and alloys in the semi-solid state at the Massachusetts Institute of Technology in 1971. Owing to the shear stress which acts on the semi-solid material during filling of the die, the viscosity of the material is reduced and the force required to fill even complex geometries is relatively low as compared to that needed for conventional processing. Depending on the material involved, the temperature level required to work the material is often significantly lower than in a conventional casting process, and the thermal stresses on dies and moulds are reduced[2,3]. The lower working temperature has also a favourable effect on the accuracy-to-size of the geometries and on the production of pore-free parts, since the solidification shrinkage is reduced due to a much less liquid fraction and the pressure maintained during solidification. This technology opens up completely new routes for processing innovative materials, e.g. particle- and fibre-reinforced composites, and for manufacturing composite or hollow parts. It is, however, questionable whether all the above mentioned potentialities of thixoforming can be exploited with aluminium alloys.

The future implementation of thixocasting in the industrial series production of high-grade components depends especially on the quality of the pre-material and efficiency of its production. In these processes, the alloys with a non-dendritic semi-solid structure can be used in order to obtain the desired fluidity and mechanical properties. The non-dendritic semi-solid structure can be produced by two routes which are: (i) a mechanical or magneto-hydrodynamic stirring, and (ii) an intensive ultrasonic treatment during solidification.

Systematic investigations to use ultrasound during the thixocasting have not been made up to now. The main aim of the present study is to investigate the possibility of use ultrasound as an effective alternative to electromagnetically produced thixotropic material. The possibility of obtaining a thixotropic structure by an ultrasonic treatment in Al–Si based alloys was investigated. Silicon is one of the few alloying elements that does not increase the density of the alloy. Due to the very high hardness of Si crystals dispersed in the matrix the wear resistance of Al–Si based alloys is very high. Aluminium and silicon constitute a simple binary eutectic system with the eutectic point at 12.2 at.% and 577°C. Most Al–Si based alloys being used are hypoeutectic, but hypereutectic alloys are attractive to the automotive industry and desirable for wear resistant applications, where high strength and low weight are also required.

The present investigation attempts to evaluate the

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effect of an ultrasonic treatment on the microstructure of hypereutectic Al–Si based alloys.

Experimental

In our experiments, we used alloys with Si concentrations of 13.8 and 17.1 wt.%. The chemical composition of the alloys is given in *Table 1.*

At the higher silicon content, the alloy melting point increases due to the steep slope of the liquidus on the silicon-rich side. Primary silicon crystals coarsen substantially, particularly due to the wide solidification range of this alloy, and impair the fracture toughness of the casting. The fluidity of the alloys was also found to decrease beyond 18 wt.% Si. Silicon coarsening and fluidity reduction become more significant when the silicon content exceeds 18 wt.%, and it is almost impossible to obtain a good quality casting at a conventional foundry cooling rate.

The transmission of the ultrasonic vibration to the solidifying melt is not an easy problem because a resonator can rapidly fail under the effect of temperature and cyclic stresses[4]. Dobatkin and Eskin[5] used ultrasound intensities in the range of 7–20 W cm^{-2} and found that carbon steel resonators were dissolved quickly in liquid aluminium, whereas 18 wt.% Cr–9 wt.% Ti steel resonators have a life time of only 1–2 min. Niobium alloys proved to be more resistant[6]. Laboratory tests were based on the use of special benches where ultrasonic vibrations were fed to the solidifying melt by a top transmission method. An ultrasonic generator of 10 kW and a magnetostrictive transducer were used in those tests. The ultrasonic treatment was carried out in a cylindrical ceramic crucible of approximate dimensions 80 mm diameter and 160 mm height. The thermocouple was positioned to record the temperature of the melt between the centre of the charge and the crucible wall, i.e. 30 mm from the crucible wall.

To study the thixotropic behaviour, ultrasonically treated and non-treated specimens were upset in an electro-hydraulic press under semi-solid conditions. The specimens measuring 20 × 20 × 10 mm were deformed at 580°C after heating and holding for 15 min. During the deformation the height of the specimens was decreased down from 10 to 5 mm. The variation of the deformation load during the upsetting was measured. Tensile tests were done with an Instron machine at a loading rate of 0.5 mm min^{-1}. The tensile specimens had a working length-to-diameter ratio equal to 10.

Table 1 Chemical composition of the alloys (in wt.%)

Alloy	Si	Cu	Mn	Al
AlSi13	13.8	3.1	0.3	Balance
AlSi17	17.1	4.5	0.55	Balance

Results and discussion

It was revealed that an ultrasonic treatment additionally superheats the melt in the core compared with the casting process without ultrasonic treatment (*Figure 1*). The microstructure changes in the solidifying metal are generally due to the processes in the melt and the two-phase liquid-solid zone, i.e. crystal nucleation, dispersion and mixing. These processes depend on the cavitation and streaming as well as processing factors and material properties. The shock waves appearing during the collapse of the cavitation bubbles caused some crystals at the solidification front to break down and move towards the liquid bulk. In addition to breaking down the growing crystals, the ultrasound also affects the nucleation rate. Simultaneously, an ultrasonic treatment of the melt reduced the undercooling from 2.1 to 0.3°C. The changes of cooling curves show that the nucleation takes place more easily. There are two possible mechanisms of the cavitation effect on the nucleation rate. Cavitation activates insoluble particles (e.g. oxides or ultrafine particles of some intermetallics) existing in the melt, and turns them into solidification sites. The fragments of destroyed dendrites also act as solidification sites. Another mechanism is the following[7]. During the expansion half-period, the bubble rapidly increases in size, and the liquid evaporates inside the bubble. The evaporation and expansion tend to reduce the bubble temperature. A decrease of the bubble temperature below the equilibrium temperature results in an undercooling of the melt at the bubble surface, and hence in the probability that a nucleus will be formed on a bubble. The ultrasound also prevents

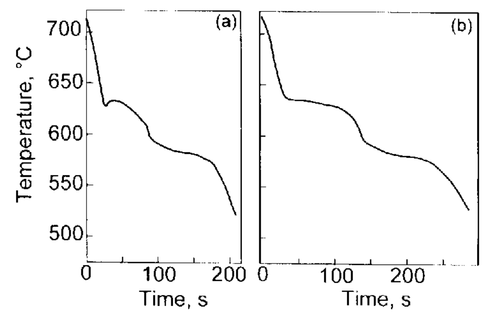

Figure 1 Cooling curves for AlSi17 alloys solidified conventionally (a) and during ultrasonic treatment (b)

Table 2 Effect of the casting technique on the mechanical properties of hypereutectic Al Si based alloys

Alloy	Casting technique	Tensile strength [MPa]	Elongation [%]	Hardness [HB]
AlSi13	Conventional casting	185	0.5	98
AlSi13	Conventional casting	210	1.5	96
AlSi17	Conventional casting	160	0.5	102
AlSi17	Conventional casting	180	1.2	98

Table 3 Effect of an ultrasonic treatment (UST) on the true stress σ_s during deformation at 580°C

Alloy	σ_s, MPa		$\sigma_{sUST}/\sigma_{sCC}$
	Conventional casting (CC)	Casting with UST	
AlSi13	29	20	0.69
AlSi17	51	42	0.82

the agglomeration of individual nuclei into a polycrystal during their growth in the semi-solid alloy. At high temperatures, above the grain boundary wetting phase transition temperature, the liquid phase wets all grain boundaries and can stop the agglomeration of single crystals[8]. However, the liquidus temperature of the Al–Si based alloys studied is rather low, and a mechanical stirring or an ultrasonic treatment is required for a refinement of the microstructure.

In hypereutetic AlSi13 specimens prepared with the aid of conventional casting, the primary silicon crystallizes as hexagonal plates joined together at the centre into star-shaped particles, as they appear in cross-section (*Figure 2*). By contrast, the ultrasonic treatment refined the silicon crystals and distributed them uniformly over the cross-section. Most of the silicon plates were disconnected and broken during the ultrasonic treatment, forming spheroidized crystals. The microstructure of hypereutetic AlSi17 specimens prior and after the ultrasonic treatment is shown in *Figure 3*. It is clear from this figure that the primary Si crystals have facceted morphologies prior to the ultrasonic treatment. However, the ultrasonic treatment resulted in morphological changes of the primary Si crystals from faceted to spherical. A fragmentation of large primary crystals followed by aggregation of the fragmented Si is considered to be responsible for the spheroidization of the primary Si crystals. The ultrasonically induced structure changes improve the mechanical properties at room temperature. As shown in *Table 2*, as-cast hypereutectic Al–Si based alloys showed a modest increase of the strength and a decrease of the hardness. Typically, the ultrasonic treatment results also in an increase of the plasticity by a factor of 1.2–1.5. The increase in the ductility makes hot cracking during casting less probable. In *Fig. 4* is shown the variation of deformation load during the upsetting of the specimens by 50% at the temperature of 580°C. The quantitative assessment of the true stress σ_s upon the upsetting in the semi-solid state is given in *Table 3*. It is clear from *Figure 4* and *Table 3* that the maximum stress of the upsetting is considerably lower for ultrasonically treated alloys. Probably, in this case similar to the sliding of ultrafine grains during superplastic deformation in the solid state one can observe a thixotropic sliding of non-dendritic grains under semi-solid conditions.

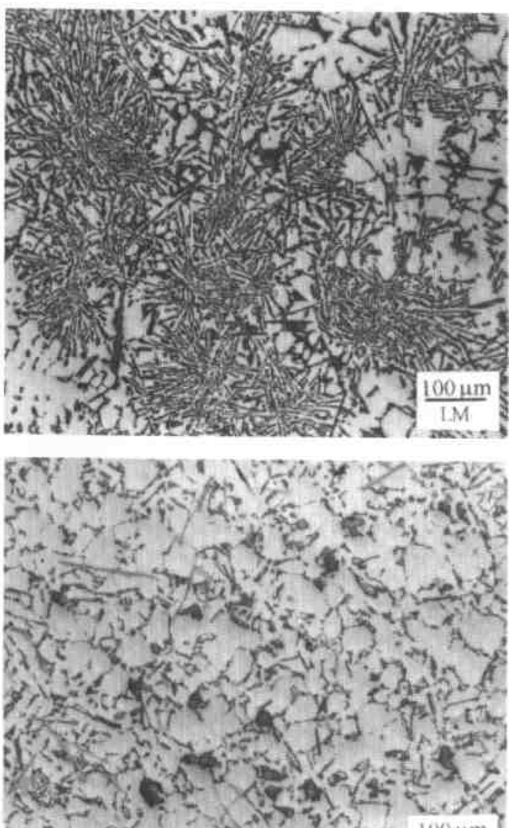

Figure 2 Microstructure of AlSi13 alloys solidified conventionally (a) and during ultrasonic treatment (b)

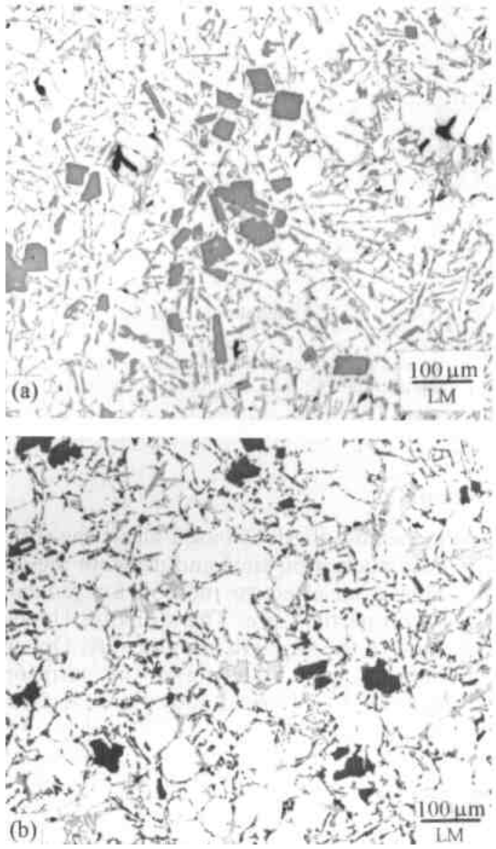

Figure 3 Microstructure of AlSi17 alloys solidified conventionally (a) and during ultrasonic treatment (b)

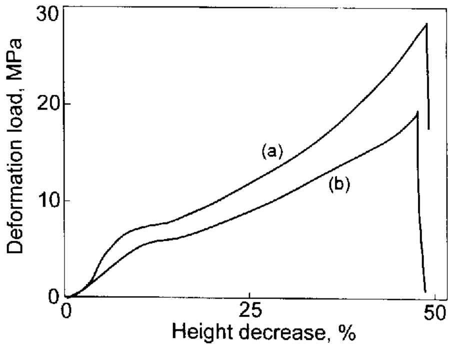

Figure 4 Variation of the deformation load upon upsetting of AlSi13 specimens at 580°C: (a) Conventional casting, and (b) casting during ultrasonic treatment

Conclusions

During the casting of Al–Si based alloys the ultrasonic field provides nucleation sites and destroys the growing crystals. This is an effective method for reducing the primary silicon particle size. The structure changes led to an increase of the strength and ductility. Our investigation confirms great advantages of ultrasonically treated ingots of Al–Si based alloys upon deformation in the semi-solid state.

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References

1 Spencer, D.B., Merhabian, R. and Flemings, M.C., *Metall. Trans.* *3*, 1972, 1925–1932
2 Gabathuler, J.P. and Ditzler, C., *Semi-Solid Processing of Alloys and Composites*. SRP, Sheffield, 1996, pp. 331–352
3 Kahl, W., *Metall 4*, 1994, pp. 295–306
4 Abramov, O.V., *Ultrasound in Liquid and Solid Metals*. CRC Press, Boca Raton, FL, 1994, pp. 251–256
5 Dobatkin, V.I. and Eskin, G.I., *The Effect of High Intensity Ultrasound on the Phase Interface in Metals*. Nauka, Moscow, 1986, pp. 87–93 (in Russian)
6 Sterritt, A., Bacon, M., Bell, F. and Mason, T.J., *Proc. Ultrasonic World Congress*, Part 2, Berlin, 1995, pp. 725–732
7 Kapustina, O.A., *The Physical Principles of Ultrasonic Manufacturing*. Nauka, Moscow, 1970, pp. 45–61 (in Russian)
8 Straumal, B., Gust, W. and Molodov, D., *Interface Science 3*, 1995, 127–132