Abstract

A comprehensive study was carried out to establish the effects of controlled stirring during solidification on the microstructure and mechanical properties of aluminium alloys, in comparison to conventionally gravity chill cast material. A novel device comprising a grooved reaction bonded silicon nitride rod rotating in a tube-like crucible was used to process aluminium alloys in the mushy state. The stir casting device was specially designed to also enable rheometric study of the alloys in this condition. A factorial design of experiments was used to determine the effect of the process variables shear rate ($\dot{\gamma}$), shear time ($t_s$), and volume fraction solid during shear ($f_s$) on microstructure and both static and dynamic mechanical properties of the stir cast alloy. Investigation of the microstructure consisted of computer-aided image analysis of the primary phase morphology. A more globular primary phase was achieved at low values of $f_s$, but this was not the optimum morphology for mechanical properties. In all cases, improved mechanical properties and reduced porosity were obtained in the stir cast condition in comparison with conventional casting and in comparison with previous work on stir casting. Comparison with alloy commercially rheocast via electromagnetic stirring, however, showed that the latter had superior mechanical properties. It is proposed that the mechanical stir casting process be considered as an alternative to gravity die casting in cases where very simple and thick walled shapes are required. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Stir casting; Aluminium alloys; Image analysis; Microstructure; Mechanical properties; Rheocasting

1. Introduction

In conventional casting processes, liquid metal is poured into a mould and solidifies as heat is extracted via the mould walls. The morphology of the growing solid–liquid interface is typically dendritic. The natural progression of filling followed by solidification often leads to internal structural defects, such as entrained oxide or shrinkage porosity, which combine to yield a casting of relatively poor mechanical properties.

Research at the MIT in the 1970s into the rheology of alloys in the mushy state, as reported in [1], generally involved use of a rotational viscometer which acted to fragment the dendritic solid morphology in a time-dependent fashion, revealing the thixotropic nature of metallic materials in this state. This work inspired three decades of subsequent research into the processing and properties of alloys in this so-called semi-solid state, the results of which are reported at the biennial international conference on the subject [2–4]. It is beyond the scope of this paper to present a comprehensive review of the field, but it should be noted that the semi-solid processing (SSP) of alloys is utilised in a number of manufacturing routes today for high quality aluminium and magnesium castings, with reduced levels of casting defects.

Over the years, a number of devices have been constructed to either investigate the rheological behaviour of semi-solid metals, or to produce billets with a non-dendritic microstructure. Rheological characterisation has typically been carried out by an active mechanical shearing method, normally using augers or impellers mounted on a central rotating shaft (e.g. [5–8]). Electromagnetic stirring (EMS), on the other hand, due in part to its high production rate, has become the main method of producing SSP billet commercially. EMS
also avoids contact of molten metal with stirrers, and in some cases the crucible, and may be easier to implement for high temperature alloys [9–12].

A more recently developed method of SSP has been termed liquidus casting or the New RheoCasting process (NRC) [13–15]. This involves pouring the alloy with a low superheat into a chilling environment to nucleate many small grains. Once held for a short period of time at semi-solid forming temperature these grains ripen and develop a non-dendritic morphology. NRC is beginning to be used commercially for gravity die casting and subsequent forming via die casting are integrated into one operation.

For the commercial production of industrial components via the SSP route, the final step is often that of high pressure die casting of mushy alloy with non-dendritic or globular morphology; a process known as thixocasting. And the process by which the requisite starting globular structure is attained has become known as rheocasting.

The thixocasting step produces near net shape products, and adds significant value to the alloy. For these reasons there have been many studies of the effects of thixocasting process variables on microstructure and properties of the product. There have also been studies carried out on the mechanical properties of rheocast materials, but these have not been comprehensive. To the knowledge of the authors, there has been no detailed quantitative study on the effects of rheocasting variables on the microstructure and both static and dynamic mechanical properties of the rheocast material. This was an oversight, because it is possible that sufficient improvements in quality and mechanical properties of alloys could be produced via rheocasting such that, in certain cases, the additional cost of thixocasting would not be justified. For example, in cases where thin walls and fine detail are not a feature of a part, rheocasting could be considered as an alternative to gravity die casting. For this reason, in addition to scientific interest, such a study was undertaken by the authors.

It was decided that use of mechanical stirring was the most direct and cost effective way of altering shear rate, and because of this, in addition to enabling rheometry, a mechanical rheocaster was designed and built. The design brief was to produce materials with a range of microstructures, from fully dendritic to fully globular. At this point a note on terminology is appropriate. The distinguishing features of the new mechanical stirrer were to include:

1. a capability for semi-continuous stir casting of aluminium alloys;
2. top feeding with liquid, and semi-solid poured in a continuous laminar stream from the bottom;
3. a well-defined shear zone in which process parameters could be closely controlled;
4. shear zone design to avoid porosity-inducing vortex formation;
5. dual purpose i.e. to act also as a rheometer;
6. use of unique rotor and crucible materials to enable continuous clean operation.

Some of these features are shared with other devices, but this stir caster is unique in its design and in that it has all of these attributes. The authors have established that at least 30 mechanical stirring systems have been constructed over the past three decades, and it is practical to cite only some examples here. The devices have been used either for rheological [5–8] or stircasting [16–18] investigations, but rarely for both. Most previous systems are also much smaller than the one presented here.

This study involved a Taguchi designed test programme to reveal microstructural features and determine mechanical properties, including toughness and fatigue performance, of stir cast materials, in comparison to conventionally cast material. In this way, the properties of the processed alloys could be related to the microstructure, and conclusions drawn regarding not only optimum microstructures, but also optimum processing conditions. Image analysis techniques were used to supply quantitative data on the microstructure. This follows the previous work on microstructural characterisation of EMS [19] and mechanically [20] rheocast alloys.

2. Experimental

2.1. Stirrer design

A mechanical stirrer/rheometer as illustrated in Fig. 1, was designed and built to produce the various cast morphologies. The semi-solid alloy was sheared in a heated tubular zone between a grooved rotor and a crucible. An independent in-line torque meter was positioned between the stirring rotor and the drive motor to enable rheological measurements. The caster furnace was heated by means of four resistance heating ele-
ments. One element around the wide reservoir at the top of the crucible and three along the lower narrow section were used to control the temperature in the semi-solid range of the alloy. This configuration enabled a maximum temperature of 850 °C and control of the temperature gradient within the narrow section of the crucible, where the shearing occurred. A linear drive provided lift to the rotor, enabling evacuation of the stir caster after the desired period of shear. During shear, with the rotor in the lower position, the device also acted as a rheometer.

The rotor and crucible (Fig. 2) were both, uniquely, of Reaction Bonded Silicon Nitride (RSBN), which enabled these two parts to be easily lapped together during operation of the stir caster. RSBN has good thermal shock resistance, good high temperature strength, does not contaminate the melt, and has a low coefficient of thermal expansion and moment of inertia.

An additional external immersion heating element was needed in the reservoir to provide sufficient molten alloy there for an adequate metallostatic head for stir casting at higher fractions solid. A batch casting trolley, which also held a plug against the crucible outlet, was used to carry the chill moulds into which the stir cast material poured. Control of stirring speed, stirring time, stirrer height, and the temperature profile of the furnace, was implemented on a PC by means of LABVIEW control software, and data input and output control boards. The software also displayed and logged the stirring speed, height of the stirrer, temperatures in the furnace, and the torque experienced by the stirrer, on a real time basis. Apparent viscosity, shear rate, and shear stress were also calculated and logged against time by the program. Detailed design, construction and operation of this stir caster have been previously described [21].

2.2. Operation of the stir caster

When setting up the stir caster before an experiment the rotor was first lowered into the crucible, Fig. 1. Its height was accurately adjusted to form a partial seal at the exit such that it was held concentrically during stirring. Only a partial sealing of the outlet was allowed to ensure that torque pick-up from the rotor-crucible interaction was negligible. An external plug attached to the batch casting trolley provided a full seal at the exit. After the caster set-up, metal melted in an induction furnace was transferred to a resistance holding furnace where it was stabilised at a temperature 20 °C above the liquidus temperature. The melt was then poured into the stir caster furnace which had been preheated to 570 °C for A356 and to 595 °C for Al–4%Si. Once the temperature of the semi-solid melt (Tss) was stabilised, giving the desired fs, via the element controllers, rotation of the stirrer was started. After shearing the alloy at the specified shear rate and for the specified length of time, the rotor was raised, the plug on the batch casting trolley was released and the alloy allowed to flow into a 35 mm diameter cylindrical steel mould, of height 90 mm.

Conventional gravity chill castings, poured from 20 °C above the liquidus, were also made in these moulds, for comparison purposes.

The resultant bars were examined radiographically. Quality indicator wire showed that a resolution of about 0.1 mm could be obtained from the procedure.

2.3. Thermal analysis

The slope of the Tss–fs curves close to the eutectic temperature affects fs control. With too small an absolute slope here, accurate fs control becomes difficult [17]. The upper limit of fs at which stir casting is possible depends on the stir casting device. For example, local solidification may occur due to a lack of accurate temperature control, or insufficient motor torque may be available to stir the more solid structure.
Higher fractions solid may be stir cast by using a relatively large liquid metal head, to provide a pressure on the semi-solid material during stir casting, and/or by keeping the caster exit well insulated to avoid local solidification. The $T_{ss} - f_s$ relationship and coherency points for the alloys under investigation, A356 and Al–4%Si, were determined using thermal analysis following the methodology of Bäckerud et al. [22]. Such thermal analysis of A356 has been carried out previously [22,23] but at faster cooling rates. A slow cooling rate of 0.06 °C s$^{-1}$ (the slope of the cooling curve after solidification) was used in this work in order to match the stabilised temperatures in the experiments. The chemical compositions of the alloys used are shown in Table 1.

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Ti</th>
<th>Ni</th>
<th>Zn</th>
<th>Pb</th>
<th>Sn</th>
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<td>0.1</td>
<td>0.4</td>
<td>0.31</td>
<td>0.12</td>
<td>0.14</td>
<td>0.013</td>
<td>0.056</td>
<td>0.07</td>
<td>0.007</td>
<td>Bal</td>
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<tr>
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<td>0.004</td>
<td>0.01</td>
<td>0.173</td>
<td>0.005</td>
<td>0.007</td>
<td>0.005</td>
<td>0.013</td>
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<td>0.006</td>
<td>Bal</td>
</tr>
</tbody>
</table>

### Table 2

<table>
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<th>$f_s$</th>
<th>$T_s$ (°C)</th>
<th>$t_s$ (s)</th>
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<td>–</td>
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<td>60</td>
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<td>630</td>
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<td>4</td>
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<td>0.3</td>
<td>601</td>
<td>60</td>
</tr>
<tr>
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<td>A356 stir cast</td>
<td>112.84</td>
<td>0.3</td>
<td>601</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>A356 stir cast</td>
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<td>0.3</td>
<td>601</td>
<td>60</td>
</tr>
<tr>
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<td>A356 stir cast</td>
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<td>601</td>
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</tr>
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</tr>
<tr>
<td>13</td>
<td>EMS rheocast</td>
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<td>–</td>
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</table>

2.5. **Metallography and image analysis**

Samples cut from the stir cast bars were prepared for metallographic examination. A final hand polish was performed on Selvyt cloth with ‘Brasso’ metal polish [26]. This final polishing stage also served to etch the Al–4%Si microstructure. A356 was etched with Keller’s reagent.

2.4. **Design of experiments**

Process parameters used for the stir casting experiments may be seen in Table 2. Those listed for A356 follow a Taguchi factorial design [24] with three factors ($\dot{\gamma}$, $f_s$, $t_s$) and two levels ($2^3$). Conventional chill cast specimens (materials 1 and 4), poured from 20 °C above the liquidus temperatures, were tested and the results compared with those obtained for the stir castings. An upper fraction solid of 0.3 was used for A356 to ensure fluid castings and a lower fraction solid of 0.25 was used to ensure that the alloy was above the coherency point (the fraction solid at which equiaxed dendritic grains start to impinge upon one another under normal solidification conditions). The levels of shear rate were chosen with the lower value about half of the upper one. Previous work (e.g. [8,25]) has shown that particle size diminishes early on during shear due to morphological disintegration, but begins to increase at extended shear times due to primary phase coarsening and coalescence. In order to avoid the latter effect, shear times were restricted to 5 min. Material 13 is commercial EMS rheocast A356 alloy from a European supplier.
The frequency of occurrence of these particles within various size ranges was also computed. The number of isolated particles per square millimetre was calculated for all the material types. An edge detect image processing filter was used to approximate the total number of primary particles. This included all particles within agglomerates or rosettes that were only lightly attached to their neighbouring primary phase particles. Dividing this by the number of isolated particles detected provided a means of approximating the average number of particles within an agglomerate. The form factor \( F \) and aspect ratio \( R \) were calculated for the isolated particles (including agglomerates) according to Eq. (2) and Eq. (3), respectively, in which \( P \) represents the particle perimeter, \( L_j \) is the length of the major axis, and \( L_n \) is the length of the minor one.

\[
F = \left( \frac{4\pi A}{P^2} \right) \tag{2}
\]

\[
R = \frac{L_j}{L_n} \tag{3}
\]

\( F \) has a value between zero and one. A value of one represents a perfectly circular particle morphology. As this value decreases from one the particle morphology becomes less circular. So the form factor can also be regarded as sphericity or roundness. A circular morphology yields a value of one for \( R \), but as the morphology of the particles becomes more elongated the value of the aspect ratio increases.

The microstructure of the eutectic phase in the A356 samples was also studied by optical microscopy.

### 2.6. Mechanical testing

A minimum of three castings was performed for each set of experimental parameters. Four tensile, fatigue, or Charpy samples could be produced from each cast bar. Where possible, specimens for a given test were taken from different stir castings. Tensile, hardness, and toughness tests were also performed on commercial rheocast EMS A356 billet (64 mm diameter) for comparison with the mechanically stir cast material. A minimum of three results was obtained for each property reading.

#### 2.6.1. Tensile, hardness and fatigue testing

Tensile tests were conducted according to ASTM B577M for tension testing of cast aluminium alloys. A Mitutoyo AVK-C2 hardness tester with a 10 N load was used to obtain Vickers hardness values for the castings in accordance with BS 427 Part 1. A Wöhler fatigue machine was used to perform the fatigue tests. These were performed at a constant speed of 53 Hz, in accordance with ISO 1143 and BS 3518 Part 2.

#### 2.6.2. Toughness testing

Plane strain fracture toughness tests were carried out on the commercially produced A356 EMS rheocast billet. A more detailed discussion of the testing procedure used has been described previously [28].

Charpy V-notch (Type A), keyhole (Type B) and powder metallurgy type (PM) test pieces were made from the cast materials, and tested according to ASTM standard E23. Standard dimensions (10 × 10 × 55 mm) were used for all Charpy specimens. Type A samples had a centrally located 2 mm deep 45° notch with a root radius of 0.1 mm. Type B specimens contained a through 2 mm hole centrally located in the specimen with a through thickness narrow slot leading to it from the specimen surface. PM specimens contained no stress raiser.

#### 2.7. Porosity assessment

Comparisons between porosity levels for chill cast and stir cast material were made from density measurements using Archimedes’ principle. Porosity levels, being too low for assessment using ISO 10040:1992, were also evaluated by microscopic examination (× 15) on a subjective scale, with 10 indicating the most sound sample and 1 indicating a sample with relatively high levels of porosity.

#### 2.8. Analysis methods—design of experiments

Due to the factorial design of the A356 stir casting experiments the results could be examined in detail for their dependency on the stir casting parameters [24]. Average effect graphs were plotted to examine the effect of processing parameters on the microstructural features and material properties. On these plots the number one on the \( x \)-axis represents the average effect of a higher parameter setting and minus one indicates the average effect of a lower parameter setting. The difference between these two averages represents what is termed the ‘main effect’ of the parameter on the property.

### 3. Results

#### 3.1. Thermal analysis

Temperature versus fraction solid graphs, as determined for the two alloys, may be seen in Fig. 3. Processing should occur between the coherency point and the eutectic point in order for the dendritic structure to be modified by the shearing action. Using the coherency point determined by the two thermocouple method [22], processing temperature ranges of 54 °C and 37 °C for Al–4%Si and A356, respectively, were found.
3.2. Metallography and image analysis

Chill and stir cast microstructures for Al–4%Si and A356 are presented in Fig. 4. A range of dendritic to globular microstructures was developed by the chosen conditions. The results from the primary phase image analysis of the variously produced microstructures are shown in Table 3. Stir cast A356, which was not chemically modified, had a course coupled eutectic structure with acicular Si particles with average length of the order of tens of microns. The EMS material, which had been modified by Sr additions of about 0.03%, had a divorced eutectic structure with rounded Si particles with average diameter of the order of a few microns.

3.3. Mechanical properties

Average material property results determined are presented in Table 4 and are related to Table 2 by means of the material number. Material 13 is EMS alloy from a European supplier. Samples obtained from a different supplier had practically identical properties.

3.3.1. Fatigue

Chill cast A356 and Al–4%Si were initially tested with a range of stress amplitudes in order to determine those which gave a fatigue life of the order of $1 \times 10^5$ cycles to failure for each alloy. These values were then used for the test programme. A356 was seen to have a higher fatigue strength during these initial tests. A stress amplitude of 134 MPa was determined and used for the A356 rotating fatigue tests and 104 MPa for Al–4%Si.

3.3.2. Toughness

Plane strain conditions were not achieved in any of the tested specimens of commercially rheocast material. Due to the size and ductility of the castings prepared in-house, the tests to determine fracture toughness were inapplicable. Similar difficulty in obtaining valid toughness results using such testing methods for a higher strength wrought alloy has recently been observed [29]. The impact toughness of the castings was, therefore, evaluated by means of the Charpy test. Details of the difficulty in obtaining toughness results and the final choice of the Charpy test for the current work have been presented earlier [28]. Conventional Type A specimens were used for Al–4%Si toughness determination. Values in the range of only 3–3.5 J were obtained using this type of specimen for the A356 samples, indicating its lack of toughness compared with Al–4%Si. Type B specimens did not produce higher toughness values for the A356 samples. Un-notched specimens, as specified for powder metallurgical materials were, therefore, used for the A356 samples in order to obtain sufficiently large values. Un-notched Al–4%Si samples bent and were pushed through the anvil on testing, and so could not be used for comparison with A356. Lateral expansion was also measured on all specimens.

3.4. Porosity

X-radiography indicated that the castings were sound. Sectioned castings confirmed the results observed in the developed X-ray films. Estimates of the relative soundness of the materials are included in Table 4. Density and porosity levels, determined using Archimedes’ principle, for the main material conditions, are presented in Table 5. A large degree of scatter was noticeable in the porosity observations.

3.5. Summary

The main effects plots, which relate microstructural features to process conditions for A356 are shown in Fig. 5. The main effects plots relating mechanical properties to process conditions are shown in Fig. 6.

4. Discussion

Here the links between the stir casting process variables and the resultant microstructure are investigated. This is followed by a study of the effects of microstruc-
ture on the mechanical properties of the specimens. This finally enables the identification of the optimum process settings to (a) produce a certain type of microstructure and (b) to induce good mechanical properties in the castings.

4.1. Structure-processing relationships

Here the microstructural features (Table 3) are related to the process variables (Table 2). For both Al–4%Si and A356, with the exception of material 3, a smaller primary phase particle size is evident in the stir cast materials versus the conventional chill castings (Table 3). For Al–4%Si, there is an increased particle density and a reduced number of particles per agglomerate, both indicating primary phase fragmentation, in the stir cast condition. Unexpectedly, there is a higher aspect ratio for stir cast material 3 than for the chill cast material 1 (compare Fig. 4(b) with (a)), and a slightly lower form factor. For A356, the particle density and the number of particles per agglomerate seem to depend on the fraction solid at which shearing took place. For high $f_s$ (materials 5–8) there is an average reduction in the density in comparison to the chill cast material 4, and a relatively high number of particles per agglomerate, whereas for low $f_s$ the opposite is true (materials 9–12). This would indicate that a greater degree of structural fragmentation has occurred in the material which has been sheared at a fraction solid of 0.25 (e.g. compare Fig. 4(e) with (d)). This is supported by all the average effects charts of Fig. 5. At low $f_s$ the average form factor is higher and the aspect ratio lower. It should be borne in mind that even under conventional conditions primary solid is less dendritic at the earlier stages of solidification.
Table 3
Image analysis results describing particle size and morphology for chill cast and stir cast Al-4%Si and A356 alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Flag</th>
<th>Average diameter (µm)</th>
<th>Isolated particle density (mm(^{-2}))</th>
<th>Average number of particles per agglomerate</th>
<th>Form factor</th>
<th>Aspect Ratio</th>
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<tbody>
<tr>
<td>1</td>
<td>CAS</td>
<td>90</td>
<td>97</td>
<td>4</td>
<td>0.34</td>
<td>1.42</td>
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<td>2</td>
<td>SAS</td>
<td>79</td>
<td>173</td>
<td>2</td>
<td>0.43</td>
<td>1.74</td>
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<tr>
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<td>SAS</td>
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<td>130</td>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>CA3</td>
<td>117</td>
<td>91</td>
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<td>0.27</td>
<td>1.93</td>
</tr>
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</table>

The material number relates to the processing parameters outlined in Table 2. The Flag code contains summary information about the material; CAS, conventional chill cast Al–4%Si; SAS, stir cast Al–4%Si; CA3, conventional chill cast A356; SA3, stir cast A356, with final letter H, high f; or L, low f; EMS, commercial electromagnetically stirred material.

As expected (Fig. 5) the main effects of increasing \( \dot{\gamma} \) are to increase sphericity and reduce aspect ratio. This trend towards a more globular primary phase agrees with the findings of other workers [6,18]. The effect of shear time on particle size and density, sphericity and aspect ratio, show that experiments were carried out...
within a timescale in which increasing fragmentation was still occurring.

In comparison with the commercially electromagnetically stirred A356 (Fig. 4(f)), the mechanically stir cast alloy has slightly smaller particle size, but a similar degree of agglomeration. The materials mechanically sheared at low $f_s$ have higher sphericity (e.g. Fig. 4(e)) than the EMS equivalent.

### 4.2. Property–structure relationships

Here the mechanical properties (Table 4) are related to microstructural features (Table 3). For both alloys there is an improvement in the mechanical properties of the stir cast in comparison to the gravity chill cast materials. A possible exception is the fatigue life for A356. The stir cast materials are also more sound than the chill cast ones. For the A356 experiments the mechanical properties were plotted against the image analysis results. No definite trends could be identified, making it difficult establish these relationships over the domain of experiments investigated. The best that can be done is to identify best and worst case mechanical properties and compare and contrast their microstructural features, as follows. For each of the mechanical properties listed for A356 stir cast materials in Table 4, the best (i.e. highest value) and second best, worst (lowest) and second worst materials were compared with their respective microstructural parameters of Table 3. For each mechanical property, if the best two materials had values of a microstructural parameter both greater or both less than the average value of all the results for stir cast A356, then this was noted. Then, for that property, the worst two materials were noted. If both these had values of a microstructural feature on the opposite side of the average to those of the best materials, then this was noted as an effect. The effects found are as follows. UTS, YS and $\varepsilon_t$ are highest for a low density of particles and a high degree of agglomeration, and UTS and $\varepsilon_t$ are highest for a high aspect ratio. These three effects combine to yield the conclusion that higher static mechanical properties are achieved in materials that have a less fragmented structure (e.g. material 5 in Fig. 4(d)). It is more difficult to relate toughness and fatigue life to these microstructural parameters. However, the only strong trend, across all experiments, of interest in the stir cast A356 is actually between two of the properties in Table 4—fatigue life and soundness (Fig. 7). Although soundness is included in Table 4, it could equally be considered to be a microstructural feature—it is assessed via examination of a sectioned casting. Unfortunately, no link between porosity levels and microstructural features can be established.

The EMS A356 had superior mechanical properties, most notably $\varepsilon_t$ and toughness, to those of the stir cast materials. It is thought that this was largely due to an optimal microstructure in the eutectic phase [30] and slightly lower porosity in the EMS alloy.

### 4.3. Property–processing relationships

As noted in Section 4.2, there is a general improvement in mechanical properties and soundness in the stir
Fig. 5. Average effects plots of stir casting parameters on microstructural parameters for A356.

cast over the conventional chill cast condition, for both alloys. The more globular primary solid structure in the mushy stir cast material would be more favourable to liquid penetration for feeding, in comparison to a more tortuous route through dendritic solid in the conventional process. Also, less shrinkage and associated porosity is expected in the stir castings because pouring occurs at a temperature below the liquidus.

In Section 4.1 it was noted that alloy A356 stirred at low $f_s$ and for long $t_s$ has a high degree of microstructure fragmentation. But in Section 4.2 it was noted that the static mechanical properties are best for the less fragmented structure. By superposition, therefore, it is postulated that the material processed at high $f_s$ and for short $t_s$ has better mechanical properties. Due to the design of experiments approach, it is possible to link the outcomes to the principal variables via the main effects plots of Fig. 6. Indeed, Fig. 6(a–d) back up the casual link made above. A strong relationship between microstructural parameters and either toughness or fatigue life could not be ascertained for the A356 stir castings in Section 4.2, and indeed the resultant dependence on fraction solid is lower for these properties (Fig. 6(e and g)).

Fig. 6(h) shows that fraction solid has a significant effect on porosity of the stir cast material, with greater porosity at the higher level of fraction solid. This may be due to a greater degree of air entrapment as the less fluid material exits the device. Much lower levels of porosity are evident in all stir cast material in comparison to the conventional chill castings (Table 4).

4.4. Benchmarking of mechanical properties

Considerable improvement in mechanical properties of stir cast A356 has been observed over the gravity chill cast condition. Material 4 in this work has very similar properties to those reported in the literature for
permanent mould cast A356 [31]. Material 13 also has very similar mechanical properties to those reported elsewhere for commercial EMS rheocast material [32]. This agreement with other available results serves to calibrate and thereby validate all of the present work. The stir cast alloy also has UTS and YS values quite similar to those reported (e.g.[33]) for as-thixocast material. However, the ε values for the latter are typically higher, usually in excess of 10%.

5. Conclusions

A novel stir caster/rheometer has been designed and built for processing aluminium alloys in the mushy state. In controlled experiments, stir cast A356 alloy showed significant improvement in mechanical properties and reduced porosity in comparison to conventional gravity permanent mould (chill) castings. The microstructure of conventional and stir cast material

Fig. 6. Average effects plots of stir casting parameters on measured properties and recorded observations for A356.
has been quantified by computer-aided image analysis. It has been shown that static mechanical properties are a function of microstructure, which has been successfully related to process variables. In particular, these properties are at their maximum for a low degree of primary phase structural breakdown, and this occurs at high $f_s$, low $\gamma$ and $t_e$. Materials with a more globular primary phase structure have lower mechanical properties. Fatigue properties of the stir cast alloy vary inversely with porosity. The mechanical properties of the new stir castings are not as good as the same alloy commercially rheocast using EMS, but have a very similar primary phase morphology. Differences in porosity and eutectic phase microstructure could explain these differences. The stir cast material also has twice the Fe content than is contained in the EMS equivalent, and an unmodified coarse/coupled eutectic Si. Both of these features promote easy void formation and fracture when the material is stressed. Fe content is also known to hinder fluid flow in the mushy state and promote microporosity. Careful design of the stir casting process, however, yields superior material than that produced in other stir casting work, e.g. [25], and static mechanical strength equivalent to thixocast material, albeit with lower values of elongation and ductility.

Rheometric experiments are currently being carried out by the authors on the alloys stir cast in this work.

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References