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Hot isostatic pressing of cast SiCp-reinforced aluminium-based composites

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Abstract

Two as-cast SiC particulate reinforced composites were treated by hot isostatic pressing (HIP) under different pressures and temperatures. The microstructures and tensile properties of the composites were characterized in the as-cast and HIPped conditions to study the effects of the HIP treatment. It was found that ductility of the as-cast composites was increased greatly by the HIP treatment but the yield stress was reduced drastically. The reduction of internal defects was identified to be the major factor for the improvement of the ductility. After the T6 treatment, the HIPped specimens were better than the as-cast specimens in strength as well as in ductility. The effects of the HIP temperature and pressure were also studied, and it was found that in the chosen temperature range of 450–550°C and pressure range of 100–150 MPa, increasing the temperature tended to improve the tensile properties, whilst increasing the pressure had little effect on the strength and ductility. © 1997 Published by Elsevier Science S.A.

Keywords: Hot isostatic pressing; Silicon carbide; Particulate reinforced composite; Aluminium

1. Introduction

SiC particulate reinforced composites are potentially attractive engineering materials, both solid-phase and liquid-phase processing methods having been used to produce such composites. The latter method has been used widely in industry due to its inherent advantages such as large production capacity and cost efficiency [1]. Stir-casting is amongst the most commonly used liquid-state processes. However, particulate reinforced metal matrix composites (PMMC) are produced by casting are usually low in ductility and toughness [2], the poor mechanical properties being caused mainly by internal casting defects such as porosity and particle clusters [3]. Some of the defects may be healed by secondary processes [4]. Hot isostatic pressing (HIP) has been employed as a secondary process for decades [5], but little is known about its effects on the microstructures and properties of PMMC. In the present work, two cast PMMCs were HIPped using different HIP parameters, and the effects of HIP treatment were identified by studying the changes in microstructures and mechanical properties.

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2. Experimental procedure

2.1. Cast composites

Two commercial composites, designated F3S.10S and F3S.20S, were used in the present study. They have the same matrix (aluminium alloy A359) and the same type of reinforcement (SiC particles); but the volume fractions and sizes of the reinforcement particles were different, as shown in Table 1. The composites were prepared by conventional stir-casting, Stahl molds (ASTM-B108-85a) being used to produce cylindrical bars of 18 mm diameter.

2.2. Hot isostatic pressing and heat treatment

The two composites were HIPped using the Kobelco System 5X-S. HIPping was performed for a fixed length of time (1 h) in the same protective gas (argon), but the pressure was varied within the range 100–150 MPa and the temperature within the range 450–550°C, to give five different combinations of HIP parameters, as shown in Table 2.

Some samples were subsequently heat treated to the T6 specification. This involved solution treatment for 16 h at 538°C, water quenched at above 65°C, and artificial aging for 5 h at 160°C.
2.3. Tensile testing

Tensile specimens of 6 mm diameter and 30 mm gauge length were tested at room temperature in a Instron testing machine at a cross-head speed of 0.5 mm min⁻¹. An extensometer was attached to the gauge section to give an accurate reading of the displacement. For the purposes of comparison, each composite was tested in four material conditions, i.e., as-cast, cast-HIPped, as-cast/T6, and HIPped/T6 conditions. For each material condition, two specimens were tested.

2.4. Metallography and fractography

Metallographic samples were etched in 0.5% HF solution. The porosity levels were measured at 200 × magnification using a Leica Q520 image analyzer. The fracture surfaces of the tensile specimens were studied using the Cambridge 360 scanning electron microscope.

3. Results and discussion

3.1. Effects of HIP on tensile properties

Yield stresses at 0.2% offset strain, ultimate tensile strengths (UTS) and elongations were obtained for all of the specimens tested. Fig. 1 shows some results of the tensile tests, whilst Table 3 provides details of the values obtained.

It can be seen from the above figure and table that the most remarkable effect of HIP treatment is to increase the elongation of the as-cast specimens from 1.4% to about 7%. However, the HIP treatment reduced the yield stress drastically, from 142 MPa to 74–87 MPa, and lowered the UTS slightly, from 184 MPa to 143–163 MPa. For composite F3S.20S, similar trends in changes of tensile properties were observed, but to a lesser degree. Generally speaking, HIP increased the ductility at the expense of the strength.

2.3. Tensile testing

It is also of interest to note how the T6 treatment affected the tensile properties of the as-cast and cast-HIPped specimens. As illustrated in Fig. 1, the T6 treatment increased the strength of both specimens, but had a more pronounced effect on the cast-HIPped specimens.

3.2. Effects of HIP on porosity

The microstructures of the two composites in the as-cast condition were observed to consist of primary α-Al, Al–Si eutectic, SiC particles, intermetallic compounds such as Mg₂Si and spinels (due to the secondary alloying elements and impurities). After HIP treatment, the same phases were observed in the microstructures. Two changes, however, were noticed: most of the silicon crystals were partially spheroidized; and secondly, most of the pores and shrinkages were removed. Fig. 2(a) shows an as-cast microstructure with large pores, whilst Fig. 2(b) shows the HIPped microstructure without any visible discontinuities.

Observation of the reduction in porosity was substantiated by quantitative measurement of the porosity levels, as shown in Table 4. It can be seen that HIP treatment reduced the porosity levels effectively from 1.2–1.9% to below 0.5%. This improvement can be attributed to the diffusion bonding of adjacent pore surfaces as the composites were under high isostatic pressure and temperature during the 1-h long HIP treatment.

3.3. Effects of HIP pressure and temperature on the tensile properties

HIP treatment was observed to increase the ductility and decrease the strength of the as-cast composites. There are two possible reasons for the changes in tensile properties: firstly, the reduction in porosity level; and secondly, matrix softening. There is no doubt that matrix softening had occurred at the high HIP temperatures (450–550°C). This is evidenced by the HIP treatment reducing the yield stress drastically (see Table 3 and Fig. 1). The decrease in strength can be considered to be due largely to the softening effect. However, the increase in ductility should be viewed as a combined effect of matrix softening and the significant reduction in porosity level. This argument is supported strongly by the following two observations. Firstly, after the T6

<table>
<thead>
<tr>
<th>Parameter set</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>450</td>
<td>450</td>
<td>550</td>
<td>550</td>
</tr>
</tbody>
</table>
treatment, the strength of the HIPped specimens was found to be greater than that of the specimens that had not been HIPped (Fig. 1), i.e. the softening effect during HIP was removed by the T6 treatment. However, the ductility of the HIPped/T6-treated specimens is still better than that of as-cast/T6-treated specimens. This increase in ductility can only be attributed to the reduction in porosity due to HIP. Secondly, if matrix softening is the dominant factor determining the tensile properties, then the yield stress of the as-HIPped specimens would be expected to decrease with increasing HIP temperature: this was observed not to be the case, as can be seen from Table 3.

Table 3 shows clearly that given the same HIP pressure (either 100 MPa for sets A and C, or 150 MPa for sets B and D), increasing the HIP temperature (from 450°C for sets A and B to 550°C for sets C and D) led to a higher yield stress. Table 3 also shows a similar trend for the UTS. The increase of strength with increasing HIP temperature can only be the result of a greater reduction of the porosity levels at greater HIP temperatures. At a fixed pressure, plastic deformation and diffusion bonding can take place more easily at a greater temperature, leading to a greater reduction in porosity.

Set A is the same as set B in temperature (450°C) but is different from set B in pressure (100 MPa for set A and 150 MPa for set B). Table 3 shows that the tensile properties for sets A and B are generally the same. Similarly, at a fixed temperature of 550°C, increasing the pressure from 100 MPa (set C) to 150 MPa (set D) does not result in large changes in the tensile properties (Table 3). Therefore, it can be concluded that, for the composites studied, changing the HIP pressure within the range of 100–150 MPa had little influence on the tensile properties.

It is of interest to note that whilst the HIP treatment increases the ductility considerably, after the T6 treatment the beneficial effect of HIP on the ductility is greatly reduced (Fig. 1). This phenomenon can be explained using the Griffith equation:

\[
\sigma_c = \left( \frac{4E\gamma_c}{\pi(1-v^2)} \right) \frac{1}{X}
\]

where \(\sigma_c\) is the critical fracture stress, \(X\) is the size of a fracture-initiating microcrack, \(E\) is Young’s modulus, \(v\) is Poisson’s ratio, and \(\gamma_c\) is the effective surface energy of the matrix. It should be emphasized that the fracture stress \(\sigma_c\) is the local fracture stress rather than macroscopic fracture stress. It is well established that brittle fracture is tensile-stress controlled and occurs when the value of \(\sigma_c\) is attained. Before the T6 treatment, the HIPped specimens have low a yield stress, so that large deformation is needed to attain the \(\sigma_c\) value, and the ductility is thus large. The T6 treatment increases the yield stress considerably, so that a smaller deformation is needed to attain the value of \(\sigma_c\), leading to reduced ductility.

The Griffith equation can also be used to explain the increase of ductility due to HIPping. As the HIP treatment reduces defect sizes, the values of \(X\) in the Griffith equation will reduce, thereby increasing the value of \(\sigma_c\). Since the HIP treatment reduces the yield stress drastically, a much larger deformation is needed to attain the increased \(\sigma_c\) value in the matrix, resulting in greatly improved ductility. The improvement in ductility due to HIPping was also observed in the fractographic study.

![Fig. 1. Stress–strain curves of composite F3S.10S in different conditions.](image_url)
Fig. 2. Optical micrographs showing: (a) large pores in the as-cast microstructure of composite F3S.20S; and (b) the improved microstructure after HIP.

The fracture surfaces of tensile specimens in the as-cast condition were observed to be quasi-brittle with large shallow dimples (Fig. 3(a)). In contrast, the fracture surfaces of as-HIPped specimens appeared to be more ductile, with deeper dimples in the matrix (Fig. 3(b)). For both as-cast and HIPped specimens, the fracture mode was found to be intergranular predominantly and the SiC particles were observed either to break or to debond from the matrix (Fig. 3).

4. Conclusions

Two SiC reinforced cast composites were HIPped using different parameters, the effects of HIP on the microstructures and the tensile properties being studied. HIPping was found to greatly improve the ductility of the composites. The reduction of internal defects was identified as the major reason for the improvement of the mechanical properties.
Fig. 3. SEM fractographs of composite F3S.10S: (a) a quasi-brittle fracture surface in the as-cast condition; and (b) a more ductile surface with many dimples in the HIPped condition.
Table 4  
Porosity levels in the as-cast and HIPped conditions

<table>
<thead>
<tr>
<th>Composite</th>
<th>As-cast (%)</th>
<th>Cast/HIPped (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3S.10S</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>F3S.20S</td>
<td>1.9</td>
<td>0.4</td>
</tr>
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</table>

References


