High pressure die casting (HPDC) of advanced reinforced aluminium alloys

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An advanced material based on a AlSi8Cu3Fe alloy reinforced with 6%wt. of Titanium Diboride (TiB_2) particles was employed to produce demonstrator clutch discs and to compare the obtained properties with those of the corresponding non reinforced alloy. The new material was produced through an in-situ reaction in which two salts were incorporated into the aluminium alloy melt to produce the reinforcing particles through an exothermal chemical reaction. The material so formed was first used to obtain samples through the direct Squeeze Casting technology at lab scale.
Afterwards, it was also employed to produce some demonstrator prototypes with a conventional industrial High Pressure Die Casting (HPDC) equipment. Results obtained with the reinforced material with the Squeeze Casting and HPDC technologies are presented and compared to those obtained with the corresponding non reinforced equivalent. The effect of the TiB_2 particles was analysed in terms of enhancement of mechanical properties at high temperatures, thermal properties, processing, etc.
Minor changes had to be implemented in the moulds and equipments used to produce the final samples and components. The melt was stirred in order to avoid the settling phenomenon that might have taken place due to the difference of the density of the particles and the alloy.
The processing parameters had to be fixed in order to take into account the different viscosity, castability and solidification pattern of the new material.
Information on the optimization of the casting processes and properties of the Squeeze Casting and HPDC samples obtained are shown.

Parole chiave:
High Pressure Die Casting (HPDC), Squeeze Casting, Titanium Diboride (TiB_2), Metal Matrix Composites (MMC), In-situ composites

INTRODUCTION

The need of new light materials that can comply with the more and more demanding mechanical and thermal requirements for transport applications is being an important driving force for the research on advanced aluminium alloys. The use of Metal Matrix Composites (MMC) is considered to be a good alternative for the substitution of several ferrous and non ferrous components as they present improved specific mechanical properties, good thermal dissipation features and excellent wear resistance. Notwithstanding all this, the use of these materials in commercial applications is not as extended as foreseen because of some drawbacks that remain unsolved, i.e. high raw material and machining costs, low ductility values. etc.
The production of new reinforced aluminium alloys through in-situ processes is seen as an interesting alternative to the traditional MMC production routes (Powder metallurgy or incorporation of ceramic particles into the metallic matrix through liquid routes). Both the cost of the process and the nature of the formed composites may minimize these problems.
The in-situ production route used to produce the selected advanced materials, involves premixing two fluoride salts and incorporating them into a melt of the desired alloy composition. The resulting self-propagating exothermic reaction gives way to the production of small sized (0.5-1.5 μm) TiB_2 particles that provide an improvement in the mechanical and thermal properties of the base alloy. Titanium diboride (TiB_2) is a ceramic material with a density of 4.50 g/cm^3 that presents a relatively high strength, hardness and wear resistance (Ref.1).The reaction of fluoride salts to produce TiB_2 particles is based on an established process used to for the production of AlTiB grain refining master alloys. London Scandinavian Metallurgical Co. (LSM) prepared the materials to be cast based on this technology. Even though reinforcement contents of up to 12%wt. can be achieved at lab scale these are not castable (Ref.2) and therefore, alloys with a content of 6%wt. were used through the study in order to produce the final components through the Squeeze Casting and HPDC processes.
An AlSi8Cu3Fe alloy was chosen that contained TiB_2 particles to carry out the comparison between the advanced material and the corresponding non reinforced alloy when processed through the direct Squeeze Casting and HPDC processes. The main goal of the study was to reach to know the feasibility of using the new advanced materials for transport applications where properties that cannot be reached with the non reinforced materials are required. Special attention was thus given to the capacity of the reinforced materials to flow and fill the moulds and to the obtained tensile properties at high temperatures as well as the dimensional stability and thermal properties.
Samples were prepared in a laboratory scale Squeeze Casting equipment consisting of a heated mould to produce cylindrical samples from which tensile specimens can be drawn and a 200Tn hydraulic press that applies pressure on the material through the filling and solidification stages. The study on the HPDC process with the reinforced materials

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was carried out in an industrial facility. A clutch disc mould was used to carry out the preliminary studies on the optimization of the process and final demonstrator components were produced with both reinforced and non reinforced materials in order to compare the different behaviour of the materials during the injection stage and the mechanical and thermal properties of samples obtained from the final components.

TECHNICAL APPROACH

The main objective of the study was to evaluate the feasibility of using the in-situ produced MMC material for HPDC and Squeeze Casting processes. The behaviour of the selected materials during the melting and casting steps was analysed and samples were produced to compare the mechanical properties of the advanced alloys with the corresponding non reinforced materials as well as to make a comparison between the direct Squeeze Casting and HPDC casting processes.
The materials used for this study were an AlSi8Cu3Fe alloy typical for die casting applications and the corresponding reinforced material AlSi8Cu3Fe + 6%wt. TiB_2 particles. The latter was provided by London Scandinavian metallurgical Co. Ltd. (U.K).

SQUEEZE CASTING STUDIES

The direct Squeeze Casting process was applied for the production of samples to compare the selected materials.
In this technology, the melt alloy is poured in a preheated mould and a high pressure is immediately applied over the liquid metal in order to fill complex shaped moulds and obtain a high solidification rate. For this purpose, the metallic mould is located in the plates of a hydraulic press and preheated before the casting stage. Once the melt alloy is poured, the pressure is applied through a ram located in the upper plate of the press, leading to the production of samples without any porosity and that have been rapidly solidified thanks to the application of high pressures and a specially designed water cooling system within the mould.
Samples manufactured through this process were cylindrical, having a diameter of near 103 mm and a height of 40 mm. Before final samples were prepared for the characterization, the casting was optimized through a preliminary study in which aspects like the stirring mechanism of the melt to avoid the settling of the TiB_2 particles, use of strontium as grain modifier and the effect of different casting temperatures (680-740ºC), two temperatures of the mould (150-300ºC) and two different pressures (50-100 MPa) were studied. Eventually, final samples were cast at 740ºC, a pressure of 100 MPa with the addition of strontium (0.01%wt.).
Once samples had been cast with the two materials selected, tensile samples were drawn and a detailed microstructure examination was carried out. The X-ray inspection confirmed the absence of any porosity in the obtained parts.

Microstructure Analysis

Porosity: No porosity could be appreaciated in any of the two materials. The application of high pressures during the solidification step of the material together with the near laminar flow of the material when pressed into the interior of the mould leads to the absence of porosity into the parts.

Distribution of the reinforcement: It had been previously reported (Ref.3-5) that the differences in density between the molten aluminium and TiB_2 particles (ρ_{Al}=2.7g./cm^3 and

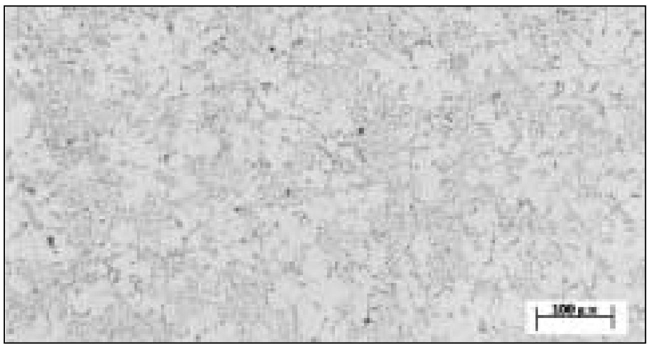

Fig. 1 – Microstructure of Direct Squeeze Casting samples. Material: AlSi8Cu3Fe + TiB_2 (6%wt.) particles.

Fig. 1 – Microstruttura dei campioni prodotti mediante Direct Squeeze Casting. Materiale: AlSi8Cu3Fe + particelle di TiB_2 (6% peso).

ρ_{TiB2}=4.5 g./cm^3) might lead to settling derived problems if no stirring is applied during casting operations. The particles might remain at the bottom of the crucible and the homogeneity of the components produced and final properties obtained could be greatly affected. In the case of the Squeeze Casting experiments, the materials were melt with an induction furnace. The microstructure analysis showed the stirring that is induced into the melt through this heating method is enough to avoid the settling up phenomenon.

Microstructure: An example of the microstructure of the reinforced alloy obtained at different casting conditions is following shown (see Fig.1). The microstructure seems to be very refined although no evidence of different grain or dendritic size can be observed with different levels of pressure. No much differences could be appreciated between the reinforced and non reinforced materials, the phases and intermetallics observed are those corresponding to the matrix alloy and the grain size is similar in both cases. The effect of the strontium addition and pressure may have masked the effect of the TiB_2 particles (Ref.2,6) as no differences could be appreciated in the size and shape of the grains. The TiB_2 particles are normally located in the grain boundaries and interdendritic regions.

Properties of samples produced by Direct Squeeze Casting

Tensile specimens were obtained from the cilindrical shaped samples with the reinforced and non reinforced materials. These samples had been produced at the following processing conditions: i) Material T: 740ºC, ii) Pressure during solidification: 100 MPa, iii) Use of strontium (0,01%) as grain modifier, iv) Degassing of the melt with argon gas and v) Accelerated solidification through the use of water as cooling agent.
The effect of the TiB2 particles can be clearly appreciated in the obtained results.
Particles provide a clear enhancement of tensile properties at high temperatures even though the deformation values are lower as foreseen (Ref.3-4,6). A decrease of down to 20% in the value of the Coefficient of Thermal Expansion (CTE) was measured that can be interesting for applications where dimensional estability at high temperatures is required. On the other hand, the reinforced material presented an increased hardness as foreseen (Ref.6-8).

HIGH PRESSURE DIE CASTING (HPDC) STUDIES

The castings were carried out in the facilities of Inyectados Gabi company (Spain) with a conventional aluminium High Pressure Die Casting equipment. The main objectives of

Table 1 – Tensile properties at different T of samples produced via direct Squeeze Casting.
Tabella 1 – Caratteristiche tensili a diverse temperature dei campioni prodotti mediante direct squeeze casting.

Material	UTS (MPa) (T_{room})	UTS (MPa) 150 °C	UTS (MPa) 250 °C	YS (0.2%) (MPa) (T_{room})	Strain (%) (T_{room})
AlSi8Cu3Fe + TiB_2 6% wt.	218-234	227.3	191.2	139-151	0.95-1.80
AlSi8Cu3Fe	223-226	175-187	NA	170-176	2.7

	Reinforced AlSi8Cu3Fe	Non-reinforced AlSi8Cu3Fe
CTE (10-6/°C)	17.2	22.0
Hardness (HB)	89	80

Table 2 – CTE and hardness properties measured.
Tabella 2 – Confronto dei coefficienti di espansione termica e della durezza misurate.

these castings were to optimize the production of components manufactured with the reinforced AlSi8Cu3Fe alloy and to obtain data to compare the behaviour and properties of this material with the corresponding non reinforced alloy.
The study was carried out in two consecutive stages. The first phase was devoted to check the behaviour of the reinforced material and adapt the casting parameters to the material and component to be produced.
A degassing FDU impeller was used that introduced NPU5 high purity nitrogen into the melt with the main goal of stirring the melt material to avoid the phenomena of particle settling.
Preliminary castings were carried out at different conditions (pressure, temperature of the metal, speed of the first and second phases) and components were machined to check the presence of internal porosity (Ref.9).
The conclusions from this first phase can be summarized as follows:

- The optimum casting T for the reinforced aluminium alloy was around 730ºC. It is advisable to keep the temperature below 750ºC to avoid agglomeration and viscosity related problems.
- The addition of strontium as a grain modifier is beneficial in order to obtain an improved microstructure. It modifies the silicon and seems to redistribute porosity (Ref.2,6).
- The TiB_2 particles seem to provide thixotropic properties to the melt (Ref.2,3,6). It has been checked that lower casting temperatures than those with the non reinforced alloy can be used to fill the mould.
- No differences were appreciated with the rest of the processing parameters tested but a large amount of slag was produced during the different steps of melting, degassing and mixing of the melt.

Once the optimum conditions had been identified, demonstrator components were obtained to carry out the analysis of the soundness and mechanical properties.
Parts were also cast with the non reinforced AlSi8Cu3Fe alloy to compare the casting behaviour and properties of both materials.
The resulting parts were visually analysed and checked by X-Ray inspection. Both analysis showed that the castings were sound even though a persistent porosity could be always appreciated in the same area of the component that was finally deemed to be due to the thickness of the part selected and the incorrect design of the mould.
The differences in the processing of the two materials were not large.
No modifications in the equipment or facilities were needed to inject the reinforced materials with the exception of the compulsory use of the degassing impeller device to make it sure that TiB_2 particles were homogeneously distributed in the final component. In fact, the reinforced material presented somehow a better castability than the AlSi8Cu3Fe alloy and lower pressures and temperatures could be used to fill the mould due to the thixotropic features provided by the presence of the TiB_2 particles.
No much differences were observed at room tamperature properties even though the positive effect of the reinforcing particles seems to be confirmed (increased properties, lower porosity levels, etc.)

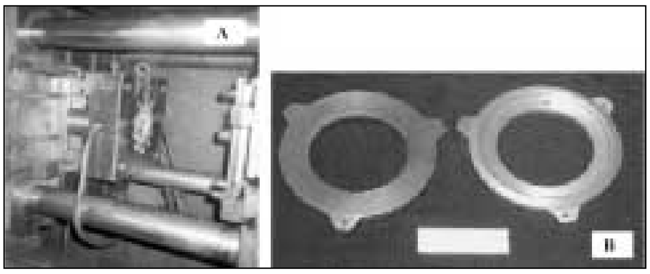

Fig. 2 – A) Demonstrator clutch disc within the HPDC mould (AlSi8Cu3Fe + TiB2 (6%wt.) particles), B) Machined component.

Fig. 2 – A) Disco di frizione dimostrativo all'interno dello stampo di pressocolata ad alta pressione (AlSi8Cu3Fe + particelle di TiB2 (6% peso) ; B) Componente dopo lavorazione.

Fig. 3 – Visual examination and checking of the presence of porosity into the final component demonstrators.

Fig. 3 – Controllo visivo e rilevazione della presenza di porosità nei componenti finali dimostrativi.

Material	UTS (MPa) (T_{room})	YS (0.2%) (MPa) (T_{room})	Strain (%) (T_{room})
AlSi8Cu3Fe + TiB_2 (6% wt.) particles	184-215	172-182	0.80-1.2
AlSi8Cu3Fe	175-195	156-166	0.9-1.3

Table 3 – Tensile properties of samples produced via HPDC.

Tabella 3 – Caratteristiche tensili dei diversi campioni prodotti mediante HPDC.

CONCLUSIONS

The feasibility of producing HPDC components with the advanced AlSi8Cu3Fe + TiB_2 (6%wt.) material was confirmed.

Handling of the reinforced alloys does not require much changes in the equipment and processes. Stirring must be provided to the reinforced alloy melt in order to make it sure that the particles are correctly distributed. Minor changes are needed in the rest of the processing parameters.

Properties obtained through the direct Squeeze Casting process are better as foreseen. The degree of internal porosity is mimimized due to the effect of the pressure applied during the solidification stage and the flow pattern of the materials into the dies (Ref.10-11).

The presence of TiB_2 particles provides an improvement in the tensile properties at high temperatures and hardness of the components. The CTE values obtained are lower and the microstructure of the parts is improved.

ACKNOWLEDGEMENTS

Part of the presented study was based on a European Project funded by the European Commission (BRST-CT-1998-5374).The authors want to thank the rest of the companies that took part of the Project (Nottingham Aluminium, Tarabusi S.A., JBTechnologies and Faseg) as well as London Scandinavian metallurgical Co. Ltd. (U.K.) for their collaboration in the production of the reinforced material and technical discussions.

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ABSTRACT

PRESSOCOLATA AD ALTA PRESSIONE (HIGH PRESSURE DIE CASTING - HPDC) DI LEGHE DI ALLUMINIO RINFORZATE

PAROLE CHIAVE:
Pressocolata (HPDC), Alluminio e leghe, Materiali compositi

Un materiale avanzato basato una lega AlSi8Cu3Fe rinforzata con particelle di Diboruro di Titanio (TiB_2) pari a 6% in peso è stato utilizzato per produrre dischi di frizione a scopo dimostrativo e per confrontarne le caratteristiche con quelle delle corrispondenti leghe non rinforzate.

Il nuovo materiale è stato prodotto mediante una reazione in-situ per la quale due sali sono stati incorporati nella colata di lega di alluminio al fine di produrre le particelle rinforzate mediante reazione chimica esotermica. In un primo tempo il materiale così formato è stato utilizzato per produrre in laboratorio campioni mediante la tecnologia di direct squeeze casting.

In seguito lo stesso materiale è stato utilizzato per produrre con procedura industriale prototipi dimostrativi mediante con un impianto convenzionale di High Pressure Die Casting (HPDC).

Nel presente lavoro vengono riportati i risultati ottenuti con il materiale rinforzato prodotto con entrambe le tecnologie di squeeze casting e HPDC e viene effettuato un confronto con quelli ottenuti con equivalenti materiali non rinforzati.

L’effetto delle particelle di TiB_2 è stato analizzato in termini di miglioramento di caratteristiche meccaniche a temperature elevate, caratteristiche termiche, processo, ecc.

Soltanto modifiche minori sono stati apportate agli stampi e agli impianti utilizzati per produrre i campioni e i componenti finiti. Per evitare il fenomeno di sedimentazione che si sarebbe potuto verificare a cause delle differenza di densità fra particelle e lega, è stato predisposto il rimescolamento del materiale da colare. Per tenere sotto controllo le variazioni che si possono determinare in termini di viscosità, colabilità e schemi di solidificazione del nuovo materiale sono stati definiti precisi parametri di processo.

Nella memoria vengono riportate le informazioni sull’ottimizzazione dei processi e delle caratteristiche della colata dei campioni ottenuti mediante Squeeze Casting e HPDC.