

Cylinder liners in aluminium matrix composite by centrifugal casting

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The reduction of car weight and fuel consumption is the strongest driving force for development and innovation in the automotive industry. A significant reduction of weight can be achieved by producing cylinder liners in Al matrix composite (Al-Al₂O₃), employing the centrifugal casting technique.

The wear resistance of this composite material, under proper working conditions, is higher than that of cast iron, which is commonly used for the production of liners.

The aim of this work is to analyse centrifugal casting process parameters in order to optimise the reinforcement distribution at the inner surface of the liner.

Parole chiave: materiali compositi, solidificazione, fonderia, metallografia, processi

INTRODUCTION

Considering the importance of reducing car weight and then fuel consumption, the re-definition of materials for engines is one of the target of cars producers. One of the recent innovations has been the introduction of cylinder liners made by the hypereutectic alloy Al-25%Si (Silitec™) [1]. These liners are produced by extrusion of billets manufactured by the Osprey technique, so their cost, significantly higher than that of cast iron ones [2], makes them an attractive (and possible) solution only for top level cars. For this reason, the development of innovative cylinder liners in discontinuously reinforced Aluminium Matrix Composites seems a very promising task. In fact, wear resistance of this composite material is very similar to that of cast iron, which is commonly used for liners; advantages obtainable from MMCs liners, in comparison with cast iron ones, can be

- weight saving (about 0,5 Kg for each liner),
- fuel consumption consequently reduced,
- lower wear rate and distortion of engine components, longer components life and lower lubricant consumption, thanks to the high thermal conductivity of the aluminium matrix.

The production of such MMCs components can be done by extrusion or using centrifugal casting [3], which presents some critical points, due to the problems correlated to reinforcement particles distribution [4]. The aim of this work is to analyse the effects of centrifugal casting process parameters on reinforcement particles distribution, in order to obtain at the liner inner surface the desired amount of them.

The Horizontal Centrifugal Casting Process

Centrifugal casting process is industrially used for production of axially symmetric components as tubes, cylinder liners, rolling mill rolls, rings and bushes with main application on iron and steel production industry and paper manufacturing. This process allows to obtain high quality castings, being associated to several advantages with respect to other foundry processes. This technique uses centrifugal

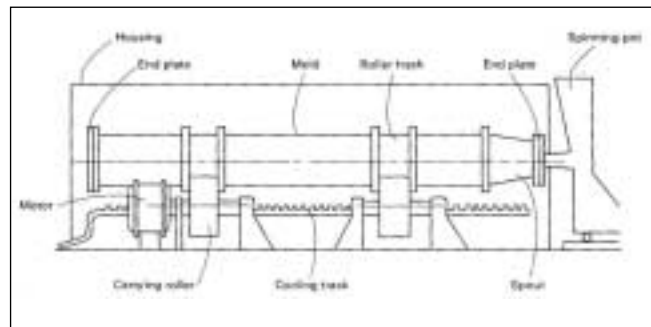


Fig. 1 – Schematic view of a centrifugal casting device.

Fig. 1 – Schema di una macchina per colata centrifuga.

force generated from rotation of a cylindrical mould around its revolution axis for "throwing" liquid metal to the inner surfaces of the mould and for solidifying it in the desired shape (Figure 1) [3].

Therefore solidification is quite rapid and a good metallurgical quality is achieved, due to two main reasons:

- solidification starts from mould inner surface, corresponding to casting outer surface, so low-melting-point impurities are carried by the solidification front to the casting inner surface,
- gas porosity is also "forced" at the casting inner surface, because of its low density.

With a simple machining operation, the inner defective surface is easily removed. Cores are not needed for obtaining the inner cavity and the "feeding" system consists of centrifugal force, that can reach up to 150 times the gravity force: additional risers are not necessary to compensate solidification shrinkage.

Functional Graded Materials

Discontinuously reinforced composites produced by centrifugal casting can be considered as Functional Graded Materials (FGMs), i.e. they are characterised by a different distribution, in radial sense, of ceramic particles as a consequence of centrifugal force effect. The different density values between ceramic particles and aluminium alloy matrix lead to a centrifugal separation: the higher density constituent migrates to outer zones and vice versa. The migration speed is controlled by the size of particles.

In other terms, a ceramic concentration profile in radial direction is obtained, that can be driven and optimised acting on process parameters, such as mould rotation speed, mould temperature, ceramic particles volume percentage and size,

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molten aluminium alloy temperature. Obviously, the ceramic particle amount profile is directly related to the hardness profile, higher percentage of hard particles determining in fact higher hardness values.

Literature [4-6] presents data and models about the effects of centrifugal casting process parameters on radial distribution of reinforcement particles. Figure 2 shows the typical reinforcement distribution in an Al-15% SiC particles (average size: 10 microns) composite, centrifugally cast in a cylindrical mould rotating at 500-1000-1500 r.p.m.. In this case, $\Delta\rho = \rho_c - \rho_m$ is positive, so ceramic amount is higher at outer zones. When a higher rotational speed is applied, it gives place to a thicker zone without ceramic particles, named particle free region. The 500 r.p.m. case does not provide enough centrifugal force to segregate the particles before solidification, and therefore there is not a significant gradient and composition is almost constant. The 1500 r.p.m. rotating speed results in three clearly distinct regions in the casting: a particle free region, a gradient region and a packed region. Changing particles size from 5 to 10, to 20 μm , the effect is the same as increasing rotational speed: larger particles have a bigger centrifugal acceleration and thus form a packed bed more easily.

Also the particle volume fraction in the raw material has a significant effect on the final particle distribution. The thickness of the particle-free zone decreases with increasing particle volume fraction, while the gradient region increases (Fig. 3). A starting particle amount of 25% gives place to the longest gradient region, in which the particle volume fraction varies from zero to the packing limit (about 40%).

Modelling the centrifugal casting process of composites

The depth (or the radial distance) from inner liner surface, at which piston pressure effect is significant can be calculated, by means of the Hertz' theory, to be about 350 μm . Thus, according to preliminary tests [7], it has been verified that a 10% volume fraction of Al_2O_3 particles gives composite material the same wear characteristics, necessary for these engine application, as those of common cast iron liners, produced from centrifugal or gravity casting. Higher alumina percentages may originate wear phenomena in the piston. Thus, at liner inner surface, a composite layer having a 350 μm minimum thickness, with a 10% vol of alumina should be produced.

Models have been developed in literature [8] for describing the motion of ceramic particles in molten alloys, during mould rotation. Symbol and units adopted are collected in Table 1.

The main hypotheses of these models, employed in the present study, are the following:

- i. The molten matrix is considered as a viscous fluid, obeying Stoke's law (the study of particles motion in a viscous liquid under centrifugal field influence is allowed).
- ii. ρ_c , ρ_m and η are time independent.
- iii. Ceramic particles are spherical.
- iv. The viscosity of the composite depends on the initial average reinforcement volume fraction (V), and is expressed as

$$\eta = \frac{\eta_0}{\left(1 - \frac{V}{V_{\text{max}}}\right)^{2.5}} \quad (1)$$

where η_0 is the matrix viscosity, considered time independent, while V_{max} is maximum packing fraction coefficient (which can be set at 0,52 for spherical particles).

The model, schematically shown in Figure 4 (in which the radial axis (x) is oriented so that to be positive for inner to outer liner surface motion), considers that on a ceramic par-

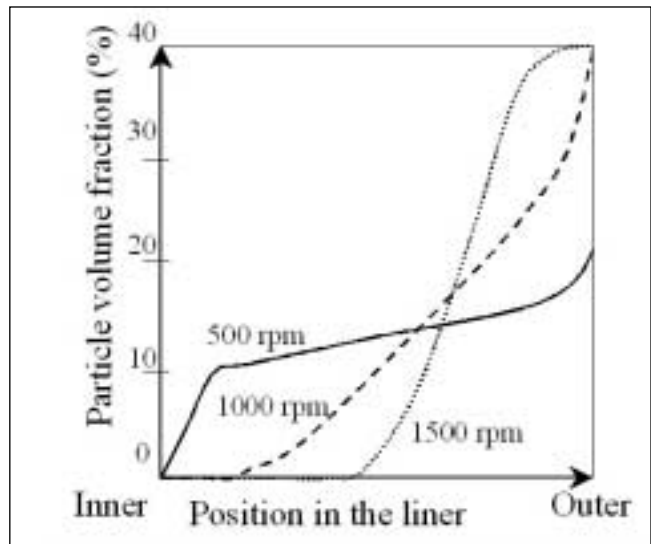


Fig. 2 – Effect of rotational speed on reinforcement distribution [6].

Fig. 2 – Effetto della velocità di rotazione sulla distribuzione del rinforzo [6].

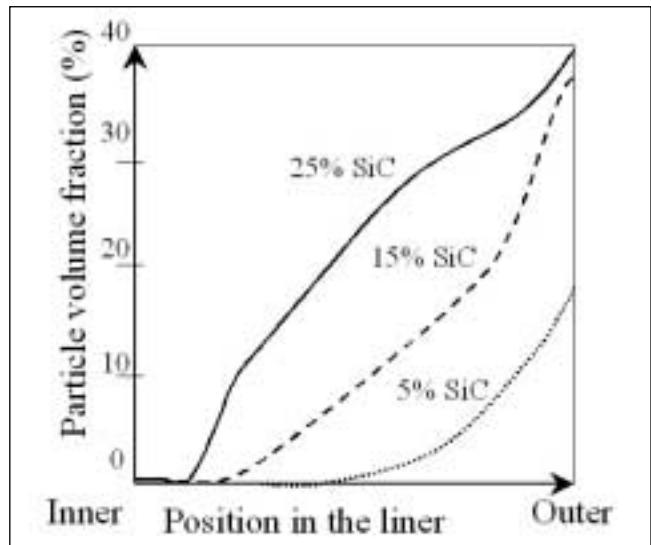


Fig. 3 – Effect of particle volume fraction on reinforcement distribution [6].

Fig. 3 – Effetto della frazione volumetrica del rinforzo sulla sua distribuzione [6].

m_c	[kg]	ceramic particle mass
ρ_c	[kg/m ³]	ceramic density
ρ_m	[kg/m ³]	matrix density
$\Delta\rho = \rho_c - \rho_m$	[kg/m ³]	density difference between ceramic and matrix
D_c, R_c	[m]	diameter, radius of particles
D_0, R	[m]	diameter, radius of liner
g	[m/s ²]	gravitational acceleration = 9,8
η	[Pa·s]	composite viscosity (liquid metal + particulate)
ω	[rad/s]	rotation speed
N	[rotations/s]	rotation speed
$G = 4 \cdot R \cdot N^2$		

Table 1 – Symbols and units adopted in models for describing the motion of ceramic particles in molten alloys.

Tabella 1 – Simboli e unità di misura impiegati nei modelli per la descrizione del moto di particelle ceramiche in leghe fuse.

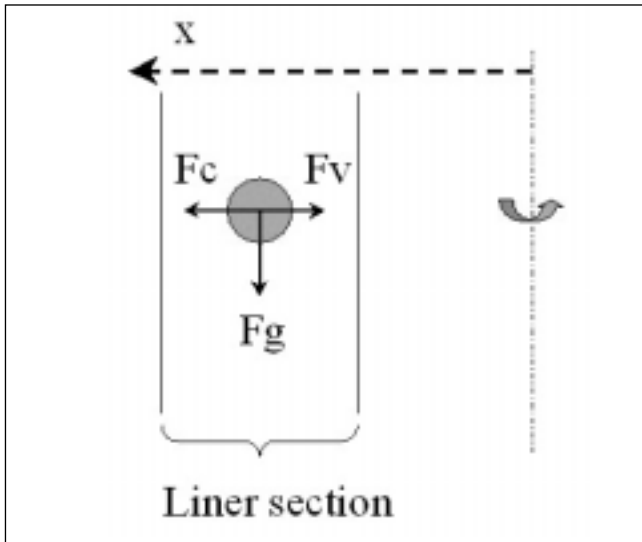


Fig. 4 – Section of a liner with an ideal ceramic particle, with the schematic view of the forces acting; the rotation axis is the same as that of cylinder.

Fig. 4 – Sezione di una canna e rappresentazione schematica delle forze agenti su di una particella; l'asse di rotazione coincide con l'asse del cilindro.

ticle, during rotation, act three main forces:

- a centrifugal force (F_c) in radial direction,
- a viscous force (F_v) in the same direction but in opposite sense, “braking” particle motion,
- the gravitational force (F_g), which can be neglected with respect to the others.

An equilibrium condition can be imposed between centrifugal and viscous force:

$$m_c \cdot \frac{d^2x}{dt^2} = |\rho_c - \rho_m| \cdot \frac{4}{3} \pi \cdot \left(\frac{D_c}{2}\right)^3 \cdot G \cdot g - 3\pi \cdot \eta \cdot D_c \cdot \frac{dx}{dt} \quad (2)$$

Solving differential equation in dx/dt , using previous hypothesis (ii), with starting conditions $dx/dt = 0$ at $t = 0$ and considering that the terminal velocity state is reached at a very early period of the centrifugal casting, it is possible to write velocity equation for particles:

$$\frac{dx}{dt} = \frac{(\rho_c - \rho_m) \cdot G \cdot g \cdot D_c^2}{18\eta} \quad (3)$$

Important information coming from the model are the following:

- the speed of particles is positive (i.e. in the same versus of centrifugal force) if their density is higher than that of matrix ($\Delta\rho = \rho_c - \rho_m > 0$);
- the speed is proportional to $\Delta\rho$, to rotation speed and mould diameter (incorporated in the term G) and to particles diameter;
- the speed is inversely proportional to composite viscosity, which, as previously shown, depends on the reinforcement percentage;
- it is possible to predict the speed of particles as well as the average time they employ for running from inner to outer surface (in the case, as that studied in this work, that $\Delta\rho$ is positive) during mould rotation.

Using the above described model, different values for the main possible process parameters can be considered (Table 2), observing the consequent effects on particles speed. It can be seen (Figure 5a-c) that particles size and volume percentage are the most important parameters affecting particles speed. Rotation speed has to be increased to very high values, in order to cause same effects of the above said parameters.

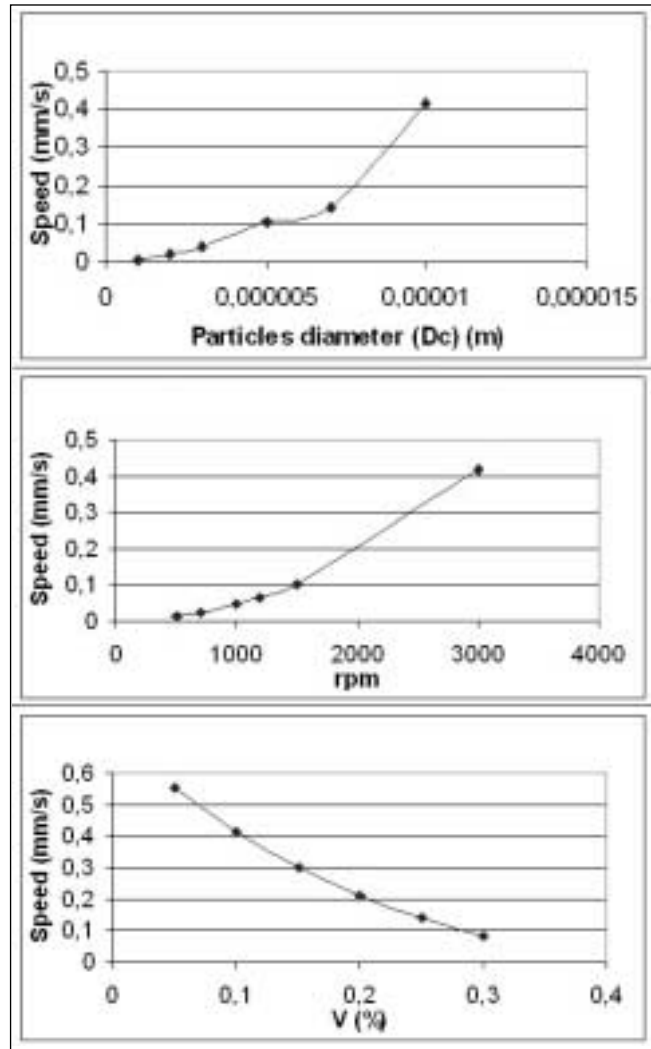


Fig. 5 – Effect of process parameters on particle speed during centrifugal casting: (a) Al-1500 rpm-30% SiC; (b) Al-30%SiC-Dc = 10 μm; (c) Al-SiC-1500rpm-Dc=10μm.

Figura 5: Effetto dei parametri di processo sulla velocità delle particelle durante la colata centrifuga: (a) Al-1500 rpm-30% SiC; (b) Al-30%SiC-Dc = 10 μm; (c) Al-SiC-1500rpm-Dc=10μm.

N (rpm)	500	1000	1300	1500
Ceramic particles	SiC Graphite	Al ₂ O ₃ TiB ₂	BN SiB ₆	B ₄ C
Particles diameter (μm)	1 10	2 20	5 35	7 75
Matrix	Al	Cu		
Reinforcement Volume %	5 30	10	15	20

Table 2 – Set of process parameters investigated by the model.

Tabella 2 – Parametri di processo considerati dal modello.

EXPERIMENTAL PROCEDURE

The centrifugal casting machine employed for this study is shown in Figure 6, where rotating mould and manual feeding system are displayed.

A first set of experiments was carried out in order to understand the solidification front motion and the average solidification time in different zones of the liner. An unreinforced

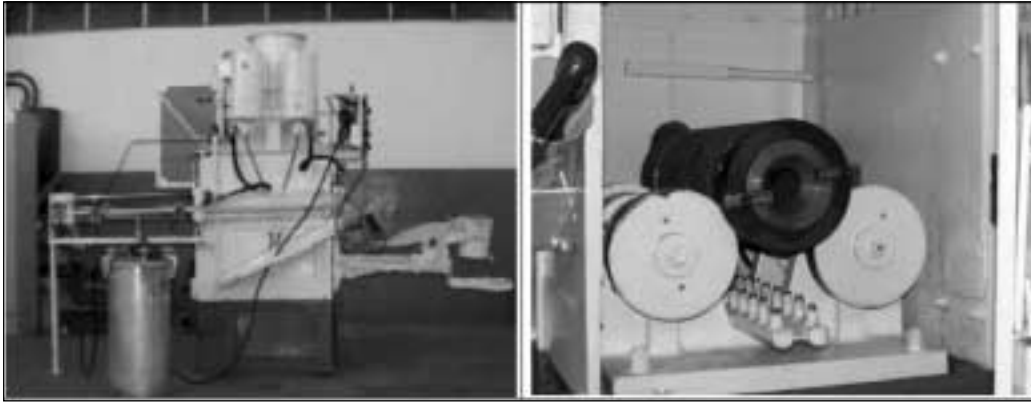


Fig. 6 – General view (left) and detail (right) of the centrifugal casting machine.

Figura 6: Vista generale (a sinistra) e dettaglio (a destra) della macchina di colata centrifuga impiegata nello studio.

Parameters	First set of experiments: Al alloy liners	Second set of experiments: AIMMCs liners
Aluminium alloy	A357	AIMMCs:W3A.10A
Mould cooling system	Not active	Not active
Mould temperature	210 °C (Test 1)- 300°C (Test 2)	See Table n.4
Alloy temperature	720 °C	See Table n.4
Mould rotation time	4 minutes	1 minute
Rotation speed	1400 rpm	1300 rpm

Table 3 – Experimental parameters.

Tabella 3 – Parametri sperimentali.

	Alloy temperature	Mould temperature
Liner A	700 °C	300 °C
Liner B	680 °C	270 °C
Liner C	730 °C	400 °C
Liner D	695 °C	400 °C
Liner E	845 °C	400 °C
Liner H	768 °C	400 °C

Table 4 – Process parameters for the production of Al matrix composites liners.

Tabella 4 – Parametri di processo impiegati per la produzione di canne cilindro in composito a matrice di alluminio.

hypo-eutectic aluminium-silicon alloy (A357: Al-7%Si-0.6%Mg) was chosen, for a better evaluation and elaboration of microstructural information. Liners were produced using two different mould temperatures, according to the parameters given in Table 3.

The production of aluminium matrix composites cylinder liners, in a second set of experiments, was carried out under the process conditions given in Table 3-4. Six groups of liners were produced adopting different values of alloy and mould temperature (T_{Al} and T_{mould} , respectively).

From a general point of view, the calculations from the model described above suggest that an Aluminium matrix composite reinforced with low-density particles (e.g. BN or B_4C) allows ceramic migration at inner surface. Such kind of powders, however, are quite expensive, especially in view of a possible future cylinder liner industrial production. Therefore, it has been decided to use the W3A.10A Duralcan composite, which is constituted by an AA3000 Al-Mn alloy reinforced by 10%wt alumina particles (with a typical size of 7-10 μm). The set of experimental conditions has been chosen to understand how the degree of particles migration can be controlled and driven, in order to avoid a too high ceramic concentration at outer zones and to optimise the process.

Using the above described model, the particles speed at a given radial distance D_0 can be computed. Considering for the liners to be produced an outer diameter of 72 mm and an inner diameter of 62 mm, taking $D_0 = 65$ mm, and implementing the processing and composite parameters shown in Ta-

bles 3-4, an average particle speed (at D_0) of 1 mm/s has been determined. Considering the liner thickness (10 mm), it is possible to calculate the average time employed by alumina particles for going from inner to outer surface: this value has been estimated to be 7 s: it will be useful to compare this value to calculated solidification time, in order to understand the correlation between migration of particles and solidification of the matrix.

RESULTS AND DISCUSSION

Al alloy liners

On the aluminium alloy liners microstructural investigations have been carried out, including the evaluation of the Secondary Dendrite Arm Spacing (SDAS) and the subsequent estimation of the solidification time (t_s), by means of the equation

$$SDAS = 11.55 \cdot t_s^{0.31} \tag{4}$$

where SDAS is expressed in μm and t_s in s (Table 5).

As could be expected, liner obtained with lower mould temperature (210°C) presents shorter solidification times. In all cases, however, the central region is characterised by solidification times 2-3 seconds longer than other regions. In both groups of liners, it has also been observed that the part near pouring zone solidifies in a shorter time with respect to the other regions.

In the inner and central zones, dendrites present a columnar structure, while in the outer ones they are equiaxed (Figure 7).

Mould temperature = 210 °C	Solidification time (s)
Outer zone	2,9
Centre	5,1
Inner zone	3,6
Mould temperature = 300 °C	
Outer zone	5,9
Centre	8,1
Inner zone	6,0

Table 5 – Solidification time in different regions of Al alloy liners.

Tabella 5 – Tempi di solidificazione nelle diverse regioni delle canne cilindro in lega di alluminio.

Fig. 7 – Microstructure in the inner (left) and outer (right) part of the Al alloy liners.

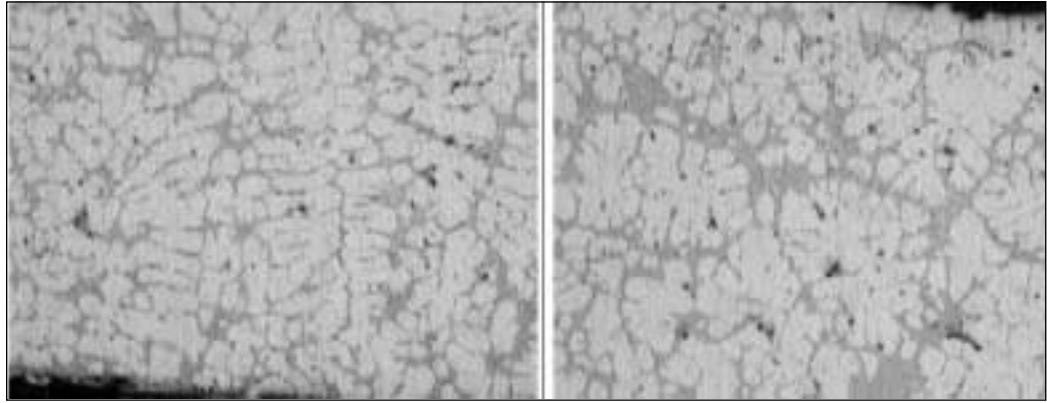


Fig. 7 – Microstruttura nella regione interna (a sinistra) ed esterna (a destra) delle canne cilindro in lega di alluminio.

Fig. 8 – Porosity (left) and surface defects (right) in Al alloy liner cast with a mould temperature of 200°C.

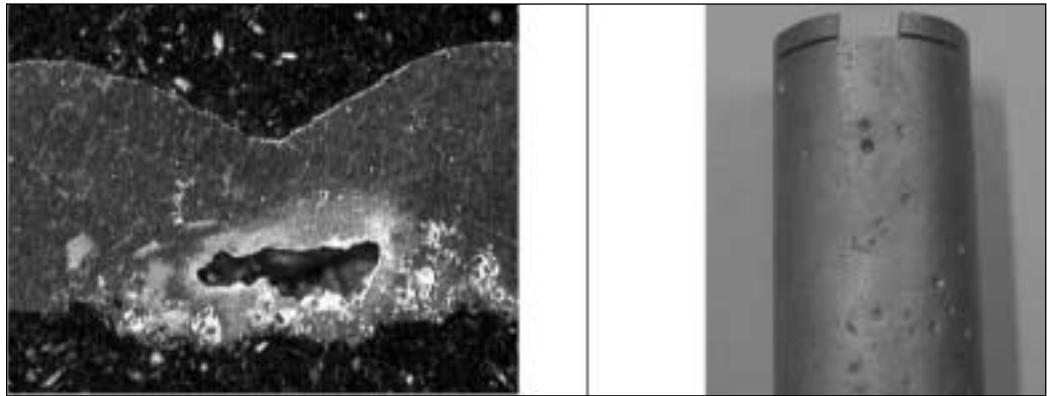


Fig. 8 – Porosità (a sinistra) e difetti superficiali (a destra) nelle canne cilindro in lega di alluminio, colate con lo stampo alla temperatura di 200°C.

Fig. 9 – Definition (a) and examples (b) of the microstructural classes achieved on the liners produced.

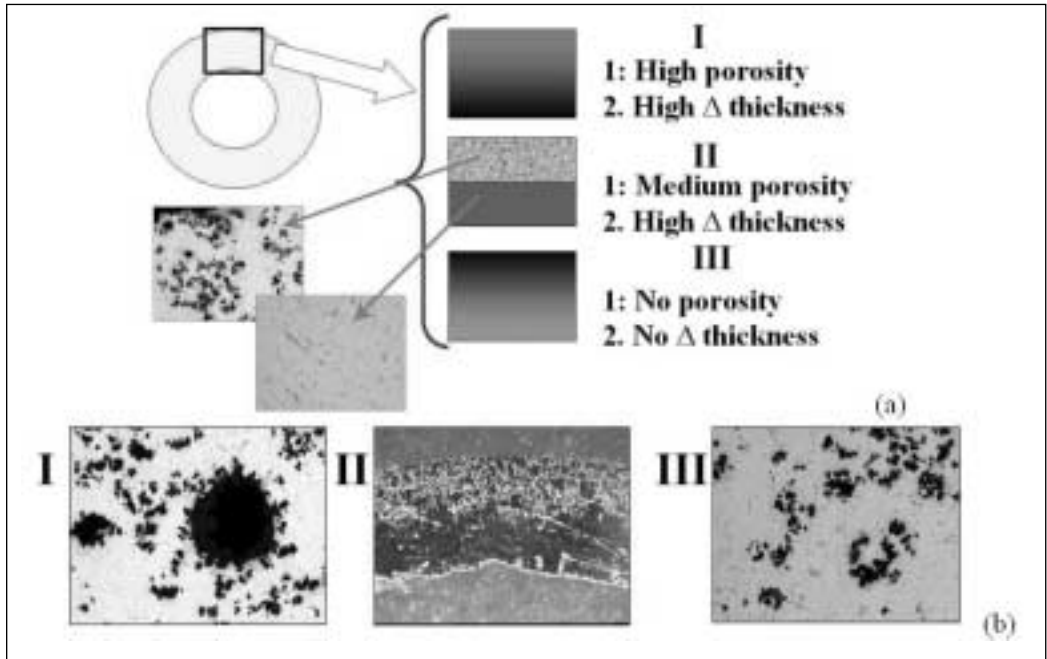


Fig. 9 – Definizione (a) ed esempi (b) delle classi microstrutturali ottenute nelle canne cilindro prodotte.

For low mould temperature, the presence of surface defects and porosity is clearly visible on liner regions far from pouring zones (Figure 8) and the thickness of liners is not constant, being higher near pouring zone. This can be explained considering that, if mould temperature is too low, aluminium has not enough time for a complete and homogeneous distribution along the mould length before solidifying. The dynamics of the solidification process can be hypothesised as follows. Firstly, molten metal enters in the mould at temperature T_{Al} , coming in contact with the cast iron mould (at temperature T_{mould}). The solidification takes place quite quickly under a temperature gradient $\Delta T = T_{Al} - T_{mould}$. A first solidified layer is originated; further liquid enters in a second time, and comes in contact with this layer (whose tem-

perature is certainly higher than that of the mould). This molten metal does not solidify soon, but it is thrown, with a helycoidal path and a turbulent flow, towards the zones sited on the opposite side with respect to the pouring area. During this motion, the molten metal decreases its temperature and entraps air. This proposed mechanism is in agreement with the surface defects and porosity location experimentally detected. A lower gradient ($\Delta T = T_{Al} - T_{mould}$) justifies longer solidification times in areas far from pouring zone. However, it seems also reasonable to consider that solidification begins at melt-mould interface; later, the air at room temperature, present inside the mould, cools the inner layer of metal, which starts to solidify. The region between these two solid layers is the last to solidify.

	High Aluminium temperature	Values of process parameters Low ΔT	Low/high die temperature (300°C/400°C)
EFFECTS DETECTED	Low porosity Particle migration towards the outer part of liners	Higher particle amount in the outer part of liners	High/low values of Δ
	Aluminium temperature LOW	Group I Mould temperature LOW	Δ temperatures HIGH
	Aluminium temperature MEDIUM	Group II Mould temperature HIGH	Δ temperatures LOW
	Aluminium temperature HIGH	Group III Mould temperature HIGH	Δ temperatures MEDIUM-HIGH

Table 6 – Correlation among process parameters and experimental results.

Table 6 – Correlazione tra parametri di processo e risultati sperimentali.

Table 7 – Correlation between microstructural classes and process parameters.

Tabella 7 – Correlazione tra classi microstrutturali e parametri di processo.

Al matrix composite liners

The data achieved from microstructural investigations have to be considered in correlation with the process parameters varied during the casting of the MMCs liners:

- Mould temperature
- Aluminium temperature
- Aluminium-mould temperature difference (Δ Temperatures).

Three microstructural and macrostructural aspects were taken into consideration as the results of the changes in processing conditions:

- the spread of ceramic percentage over the different regions of the liners,
- the difference in thickness between the part of the liner close to the pouring system and that at the other end of the mould (Δ): it should be = 0 (i.e. thickness should be uniform along the cylinder axis),
- the level of porosity.

The effects of the input variables are summarised in Table 6. According to their microstructural features, the composite liners produced can be grouped into three classes, as shown in Figure 9, and correspondingly correlated to the process parameters set given in Table 7.

The ceramic distribution pattern in the cross-section of the liners of Group I is radially uniform, increasing from inner to outer surface, but the metallurgical quality output is very poor. The effects on the outputs, in agreement with the theoretical models, are as follows.

- i. The low temperature and consequent high viscosity of aluminium leave little “freedom” to the particles, which are therefore almost uniformly distributed in the radial direction. The slightly higher concentration at internal zone is justified by the presence of clusters and by the large amount of air entrapped in them. This temperature condition also justifies the porosity. Also, the high value of Δ temperatures, by providing for fast cooling of the liquid because of the efficient heat exchange, hampers the particles' motion.
- ii. The liners made in low-temperature moulds always show significant dimensional variations.

The liners of Group II exhibit a partition line between the particle-free inner zone and the particle-rich outer zone. This behaviour can be explained as follows.

- i. The presence of the partition line is associated at the combination of a higher aluminium temperature than previous liners and at a very low Δ Temperature.

- ii. Porosity is slightly decreased, mainly in those liners where the aluminium melt was poured at higher temperatures; the dimensional quality improves too, and in some cases the objective ($\Delta=0$) is achieved. The high Δ thickness of the most part of liners is certainly caused by an improper pouring rate, as all the liners cast at the high T_{mould} of 400 °C attain excellent dimensional tolerances.

The castings of Group III show the distribution gradient to increase towards the outside, and an excellent metallurgical quality. The aluminium high temperature ensures the absence of porosity, and, due to the mould high temperature, thickness remains uniform. The low viscosity of the melt, associated to the high temperatures that are attained when casting the last two liners, allows the particles to migrate outwards, but at a lower rate than for the liners of Group II, because of the much higher values of the ΔT variable. The radial concentration profile therefore increases outwards but the distribution gradient is regular.

The statistical software package Minitab® has been used to individuate the optimum combination of the values to be given to the process parameters by means of the Design Of Experiments (D.O.E.) system. The results of the D.O.E. analysis are:

1. The porosity output exclusively depends on T_{Al} and decreases as T_{Al} increases.
2. The Δ thickness output exclusively depends on T_{mould} and improves as T_{mould} increases.
3. The "ceramic percentage on the inner surface" output depends on both temperature variables, whose combined effects should therefore be studied.

When T_{Al} is too high, the desired distribution cannot be attained; on the other hand, when it is too low, porosity problems occur; with a high T_{mould} , the dimensional characteristics are good but if it is too high, the distribution target cannot be attained.

The ideal situation might be as follows:

1. T_{Al} has an intermediate value (e.g. 750°C);
2. T_{mould} is also set at an intermediate value (e.g. 350°C);
3. The percentage of alumina in the original material must be slightly higher (e.g. 15%) to reach the 10% target at the inner liner surface: a too high alumina percentage (e.g. 20%) might cause excessive concentration on the outer surface and problems in subsequent machining operations.

CONCLUSIONS

This study has considered production by centrifugal casting of cylinder liners made of aluminium-matrix composites. The achievement of the ideal reinforcement distribution results from the combination of the main processing parameters, including casting temperature, mould temperature and reinforcement content of the composite. In particular, the optimal combinations can be represented by the following set of parameters:

1. $T_{Al} = 750^{\circ}C$;
2. $T_{mould} = 350^{\circ}C$;
3. reinforcement (alumina) percentage in the original material = 15%.

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MEMORIE

A B S T R A C T

CANNE CILINDRO IN COMPOSITO A MATRICE DI ALLUMINIO
 Prodotte mediante colata centrifuga

KEYWORDS:
 composite materials, solidification, foundry, metallography, processes

La riduzione dei pesi, e conseguentemente dei consumi, è attualmente una delle principali forze motrici dell'innovazione nell'industria automobilistica. Una significativa riduzione di peso può essere ottenuta mediante la produzione di canne cilindro in composito a matrice in lega di alluminio, rinforzato con particelle di allumina. La resistenza all'usura di questo materiale è infatti comparabile con quella della ghisa, correntemente impiegata per la produzione di canne cilindro. L'obiettivo del presente lavoro è valutare l'applicabilità del processo di colata centrifuga (Fig. 1) alla produzione di canne cilindro in composito, individuando i parametri operativi in grado di assicurare, sulla superficie interna della canna, il contenuto ottimale (10%) di particelle di rinforzo.

Un composito prodotto per colata centrifuga presenta evidentemente un gradiente di distribuzione del rinforzo, direttamente riconducibile all'entità e all'effetto delle forze agenti sulle particelle (Figg. 2-4). Vari modelli sono stati sviluppati in letteratura per descrivere questo fenomeno, tenendo conto delle variabili riportate in Tabella 1; tali mo-

delli, nel presente lavoro, sono stati applicati con specifico riferimento alle variabili sperimentalmente investigate (Tabella 2, Fig.5), determinando i "tempi di percorrenza" delle particelle di rinforzo per "migrare" dall'interno all'esterno delle canne cilindro durante per effetto della forza centrifuga.

Sono state prodotte sperimentalmente (Fig. 6, Tabelle 3-4) varie tipologie di canne cilindro, sia in lega di alluminio non rinforzata che in composito W3A.10A (Duralcan), costituito da una lega AA3000 (Al-Mn) rinforzata con il 10% in peso di particelle di allumina (dimensione tipica: 7-10 µm). Le principali variabili di processo considerate sono state la temperatura di colata della lega e la temperatura di pre-riscaldamento dello stampo; l'effetto di tali variabili è stato valutato in termini macroscopici (variazione di spessore delle canne prodotte) e microstrutturali (porosità, gradiente di distribuzione delle particelle). I risultati sono raccolti nelle Tabelle 6-7 e nella Fig. 9.

Mediante un codice di calcolo statistico (Minitab[®]) sono stati rielaborati i risultati sperimentali, individuando i parametri operativi ottimali. In particolare, la presenza, sulla superficie interna della canna di una quantità di rinforzo pari al 10%, può essere realizzata operando con temperature di colata elevate (750°C) e di stampo intermedie (350°C), ed utilizzando un composito con contenuto iniziale di rinforzo pari al 15%.

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