Mechanical and microstructural characterisation of A356 castings realised with full and empty cores

Mattia Merlin, Gian Luca Garagnani
Department of Engineering, University of Ferrara, Italy

ABSTRACT

The use of full cores, for producing automotive components by means of the permanent mould casting technique, allows good castings with a low level of defects to be obtained. Nevertheless, an extra phase of the production cycle is necessary to have an optimal emptying of the internal cavities of the castings, with an increase in costs. This scenario motivated the present research, in particular to study the effect of replacing full cores with empty cores. The component analysed is one of the three parts of a motorcycle frame, realised in aluminum alloy A356 by permanent mould casting and T6 heat-treated. Several castings have been produced with both full and empty cores; tensile strength tests have been performed on samples drawn from four different zones, in order to compare the mechanical and microstructural properties of the castings realised with the two different kinds of core. A slight decrease in elongation at fracture has been verified in the samples drawn from the castings realised with empty cores, but yield strength and ultimate tensile strength are well comparable. A finer microstructure always corresponds to higher mechanical properties; an inverse correlation between secondary dendrite arm spacing and ultimate tensile strength has been found. The effect of secondary phases, porosities and morphology and distribution of eutectic silicon particles has been considered. The Japanese Taikai methodology has been improved in order to compare the current production cycle with the one optimised by the use of empty cores. Cost, weight and time-cycle reductions in the production of the component, due to the elimination of the extra phase using empty cores, have been evaluated.

RIASSUNTO

L'utilizzo di anime piene per la realizzazione di componenti automotive, mediante processo di colata in stampo permanente, consente di ottenere getti di buona qualità con un basso livello di difettosità. Ciononostante, al fine di ottenere un completo svuotamento delle cavità interne del getto, è necessaria una fase supplementare nel ciclo produttivo con inevitabile aumento dei costi. Questo aspetto ha motivato la presente attività di ricerca sperimentale con lo scopo di studiare l'effetto della sostituzione delle anime piene con anime cave. È stata esaminata una delle tre parti di cui è costituito un telaio motociclistico, realizzato in lega A356 con processo di colata in conchiglia e trattato termicamente T6. Sono stati prodotti numerosi getti sperimentali mediante l'uso sia di anime piene sia di anime cave e sono state condotte prove di trazione su provini ricavati da quattro diverse zone di ciascun getto; le proprietà meccaniche sono state correlate con le proprietà microstrutturali per entrambe le tipologie di getto. È stata constatata una leggera diminuzione dell'allungamento percentuale a rottura sui getti realizzati con anime cave, tuttavia carico di snervamento e carico di rottura sono risultati perfettamente confrontabili. Ad una microstruttura più fine corrispondono migliori proprietà meccaniche. È stata individuata una correlazione inversa tra la distanza interdendritica secondaria e il carico unitario di rottura. È stato valutato anche l'effetto delle fasi secondarie, delle porosità e della morfologia e distribuzione delle particelle di silicio eutettico. La metodologia giapponese Taikai è stata applicata con successo sul componente in esame, consentendo di comparare l'attuale ciclo produttivo con quello ottimizzato mediante l'utilizzo di anime cave. L'introduzione di quest'ultime e l'eliminazione della fase supplementare di svuotamento consente una riduzione di costi, pesi e tempi-ciclo.

KEYWORDS

A356 alloy, permanent mould castings, sand cores, tensile properties, microstructure.

INTRODUCTION

In the automotive field the use of foundry aluminum alloys allows near-net-shape components to be produced, also for structural applications because of their high strength-to-weight ratio in heat-treated conditions. In particular, aluminum-silicon alloys have widespread applications in the field of transport because of their good castability, their corrosion resistance and their excellent recycling behaviour. Moreover, technological innovation and the increased usage of aluminum alloy could reduce emissions and energy consumption in the automotive sector. A better understanding of the relationship between microstructure and mechanical properties in cast aluminum-silicon alloys will improve foundry practice, in particular in those applications in which weight reduction is an important objective.

In their research, various authors report the effect of chemical composition and heat treatment on microstructure [1,2,3]. Also, analytical and empirical models correlating the main solidification parameters and the secondary dendrite arm spacing can be found in literature [4,5]. In A356 aluminum-silicon alloy, the secondary dendrite arm spacing (SDAS), the shape and distribution of eutectic silicon particles and secondary phases all control the tensile properties of pore-free castings [6]. The presence of Fe-rich secondary phases affects the mechanical properties of A356 alloy, in particular the ductility of the alloy. The amount and number of Fe-rich intermetallics strictly depend on the magnesium content [7,8]. Strontium additions and different solidification rates have a great effect on the microstructure; in cast aluminum alloys both yield strength (YS) and ductility are improved by the T6 heat treatment, due to the precipitation of fine β'-Mg_2Si particles and the spheroidisation of the eutectic silicon particles [9,10].

The aim of this study is to investigate the tensile properties of samples, drawn from several castings produced by the permanent mould casting technique. The component analysed is one of the three structural parts of a motorcycle frame realised in strontium-modified A356 alloy. In current production, the cavities of the component are obtained by means of two full cores and bulges could develop on the surface of the component if, during the following T6 heat treatment, only a small quantity of sand is present. Generally, the mechanical vibration of the component at the exit of the cooling tunnel is not enough to completely eliminate the sand inside the internal cavities. Therefore, in order to avoid the presence of bulges, an extra phase in the production cycle – namely "hot flogging" - is necessary to completely empty the sand.

Hot flogging determines an increase in the production costs of the component. The substitution of full cores with empty cores could eliminate the hot flogging phase. This way, less sand has to be eliminated and mechanical vibration is enough to completely empty the cavities in the component. Tensile strength tests have been performed on samples drawn from four different zones of several castings realised with full and empty cores in order to compare their mechanical properties, in terms of ultimate tensile strength (UTS), YS and percentage of elongation at fracture (A%). Microstructural features, such as SDAS and eutectic silicon particles, have been correlated to mechanical properties. In order to evaluate the presence of porosities in the castings and also in the samples, both macro and micro focus X-ray equipment have been used. In addition to metallographic inspections, fractographic analyses have also been performed on the fractured samples by means of Optical Microscopes (OM) and Scanning Electron Microscopes (SEM) with Energy Dispersive X-ray Spectroscopy (EDS), with the aim of determining SDAS, the presence of secondary phases, gas and shrinkage porosities, and of analysing the fracture profile and surface. The effect of microconstituents on crack nucleation and propagation has been evaluated. All mechanical and microstructural properties of the castings obtained with the two different kinds of core have been compared. The advantage of using empty cores to reduce time and production costs has been quantified by means of the Japanese Taikai methodology.

EXPERIMENTAL

Research has been performed on experimental castings produced to optimise the properties of the rear component of a motorcycle frame – namely "rear-frame" - obtained by permanent mould casting and shown in Fig. 1. Tensile strength tests have been carried out on samples of several castings machined from four different zones, half realised with full cores and half realised with empty cores.

Fig. 1: Rear-frame (courtesy of TFC-Galileo).

ALLOY AND COMPONENT PRODUCTION

The rear-frame castings have been produced with A356 alloy, whose wt.% chemical composition is shown in Table 1.

The alloy has been melted in an electric-induction furnace at 740 ± 5°C, then modified by adding Al-10%Sr master alloy to achieve the target strontium level of 0.02 wt.%. The chemical composition of the alloy has been analysed by means of Optical Emission Spectroscopy (OES). The melt has been degassed with nitrogen for 20 minutes, using a rotary degasser before pouring. After solidification and mechanical vibration, only the castings with full cores have also been submitted to hot flogging, that is a solubilisation at 500°C for 480 minutes. Then the T6 heat treatment has been carried out on all castings, consisting of solubilisation at 530 ± 5°C for 6h, water quenching at 80 ± 5°C and artificially aging at 145 ± 5°C for 6h.

Table 1. Chemical composition of A356 alloy (typical range of element wt.%)

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Sn	Ni	Al
	6.97	0.086	0.002	0.003	0.381	0.006	0.001	0.004	
A356	÷	÷	÷	÷	÷	÷	÷	÷	Bal.
	7.38	0.108	0.003	0.005	0.425	0.009	0.002	0.007	

CORES PRODUCTION

The sand cores have been produced starting from granular sands covered by a thermoset resin. The shell moulding technique has been used for producing both full and empty cores; the sand has been blown on a metal model, pre-heated at 230°C in order to allow the polymerisation of the resin. The difference in producing the two types of core is found in the amount of time the sand remains in the metal mould. Sand cores are very expensive, so they have a great influence on the production costs. Empty cores in this case are on average 45% lighter than full cores, with advantages in terms of environmental impact and costs.

CNC MEASURES

A tridimensional control unit has been used to measure all cores and castings and to verify their dimensional tolerances. The dimensions of the castings have been controlled after their solidification as they exit the cooling tunnel and also at the exit of the heat treatment plant; this way, possible differences with respect to nominal dimensions due to the heat treatment, are evaluated.

TENSILE STRENGTH TESTS AND NON-DESTRUCTIVE TESTS

Tensile samples have been machined from the castings in four different zones according to the Japanese norm JIS Z 2241:1998 "Method of tensile test method for metallic materials". The dimensions of the samples are reported in Table 2. In Fig. 2, two of the four drawing positions of the samples have been highlighted. In order to distinguish between samples drawn from castings obtained by full cores and samples from empty cores, they have been named Fxy-samples and Exy-samples, respectively. The subscript 'x' indicates the number of the casting and the subscript 'y' indicates the position, from 1 to 4. Tensile tests have been performed using an ITALSIGMA 20 kN testing machine and the mechanical properties have been measured according to UNI EN 10002-1:2004.

Table 2. Sample dimensions

	Over-all length	Thickness	Width of grip section	Gage length
Dimensions [mm]	60	2.5	8	25

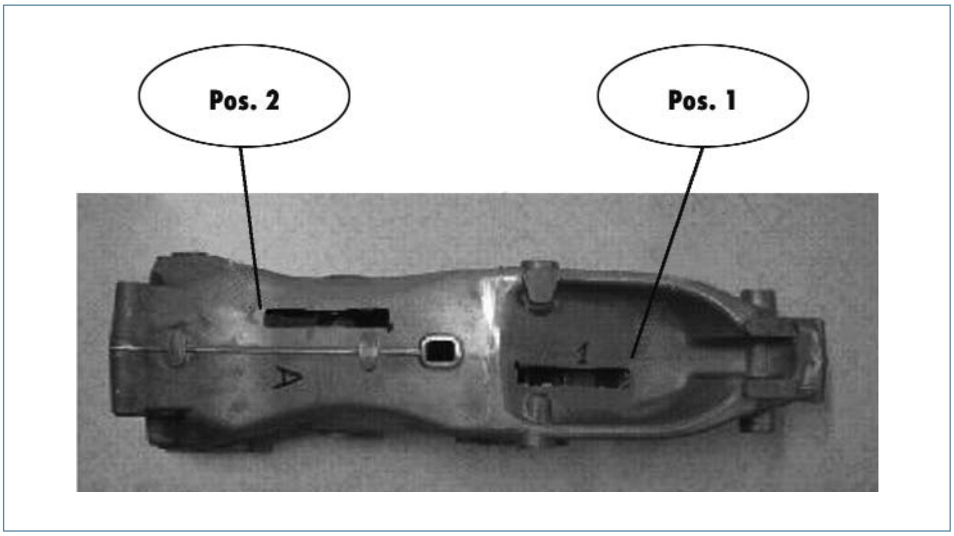


Fig. 2: The drawing positions 1 and 2 on the samples.

In order to verify the absence of macroscopic defects, macro focus X-ray equipment has been used for a preliminary analysis of the castings. Moreover, penetrating liquid tests have been carried out to control defects communicating with the external surfaces of the components.
Also the tensile samples have been analysed by micro focus X-ray equipment, which can magnify an image several times offering more definition than a conventional X-ray tube.

MICROSTRUCTURAL INVESTIGATION

Microstructural analysis has been carried out on the tested fractured samples, using OM equipped with image analysis software. Average SDAS values have been obtained by means of the linear intercept method. In each specimen, ten random areas have been acquired over the entire surface and several measurements have been taken, in order to calculate mean values. The fracture profile has been observed on the prepared metallographic section, cut out perpendicularly to the fracture surface. Important information concerning the fracture mechanism and the microstructural components involved in the crack has been obtained. Also the effect of eutectic silicon particles and secondary phases has been evaluated.

The fracture surfaces have been examined using SEM and analysis of the main precipitates has been performed by EDS.

TAIKAI METHODOLOGY

Taikai is a Japanese methodology that is useful in the evaluation of production cycles as it aims to increase the efficiency of the process according to the logic of continuous improvement. The method is composed of a series of phases. Some of these phases analyse the production layout and economical waste, others can define new improvement targets. The evaluation of the potential advantages, due to the substitution of full cores with empty cores in the production cycle, has been carried out. In particular, the percentage reduction of weights, costs and the time-cycle has been calculated.

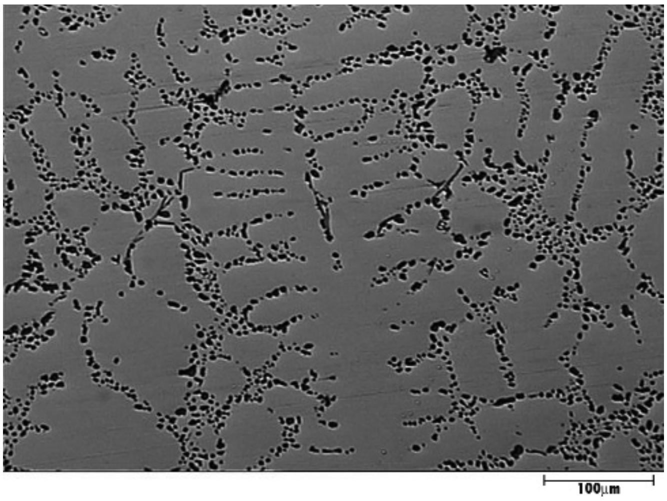
RESULTS AND DISCUSSION

MICROSTRUCTURAL ANALYSIS

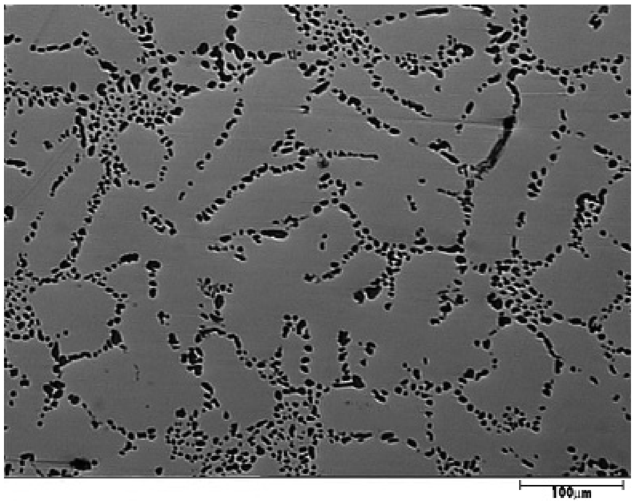
The microstructure of the components analysed consists of a primary phase, α-Al solid solution, and an eutectic mixture of aluminum and silicon. The primary phase precipitates from the liquid in the form of dendrites. The addition of strontium changes the eutectic silicon aspect ratio from acicular to fibrous. Fibrous eutectic silicon particles improve the mechanical properties of cast aluminum-silicon alloys [11]. The microstructure of the castings realised, by means of the two different kinds of core, has been compared in order to evaluate whether the different thickness of cores has a role in the microstructural and mechanical properties of the alloy.

Defects and secondary phases

Typical microstructures of samples drawn from the castings obtained by full and empty cores are reported in Fig. 3 and Fig. 4, respectively. Comparing Fig. 3a with Fig. 4a and Fig. 3b with Fig. 4b, SDAS values are in good agreement with the corresponding positions. The distribution of eutectic silicon particles is generally uniform and globular, as a consequence of the modification of the alloy and the heat treatment. Samples taken from positions 1 and 4 in castings obtained by means of empty cores show a distribution of eutectic silicon particles that is slightly less uniform than in the other positions.



A)



B)

Fig. 3: Microstructure of a casting realised with full cores: a) position 1, b) position 2.

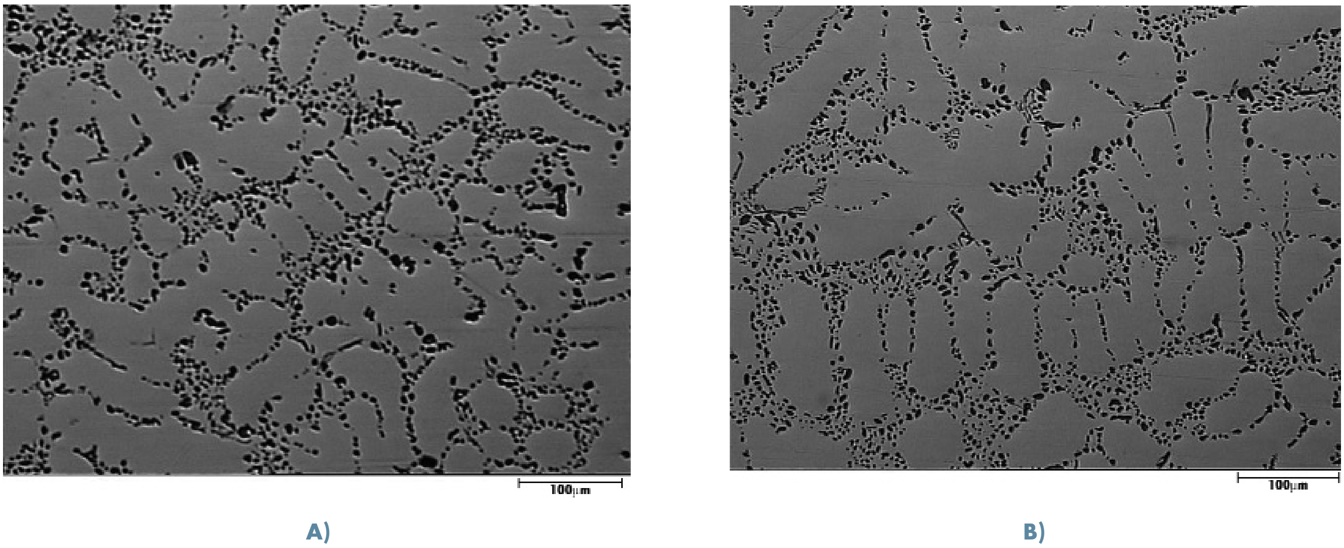


Fig. 4: Microstructure of a casting realised with empty cores: a) position 1, b) position 2.

In aluminum-silicon alloys the loss of ductility, shock resistance and machinability is usually due to the presence of Fe [12]. As shown in Fig. 5, Fe-rich intermetallics with their typical needle shape and other secondary phase particles, such as α-Al(Mn,Fe)Si phase with the Chinese script morphology, have been observed in the specimens analysed [13, 14]. Also microshrinkage and gas porosities have been found, in particular an interdendritic cavity is depicted in the micrograph in Fig. 6.

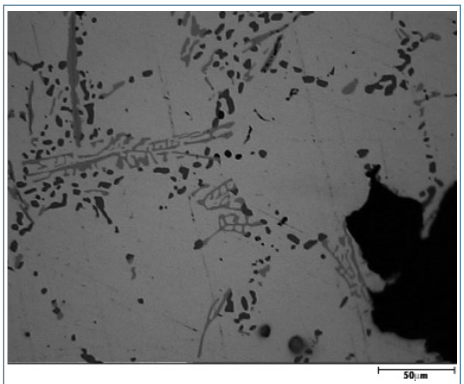


Fig. 5: Optical micrograph showing the presence of secondary phases.

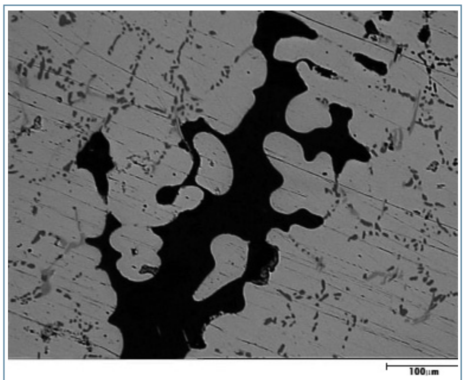


Fig. 6: Optical micrograph of shrinkage porosity.

Analysis of the fracture profile

Fracture profiles have been analysed by means of OM in order to understand the crack's growth and the effect of secondary phases better. As shown in Fig. 7, the crack crosses the interdendritic eutectic region where a significant fraction of intermetallics and eutectic silicon particles can be found. The presence of hard and needle-shaped phases determines high stress concentration. A large number of cracked silicon particles and secondary cracks parallel to the principal crack and normal to the tensile stress can be observed in Fig. 7 and Fig. 8.

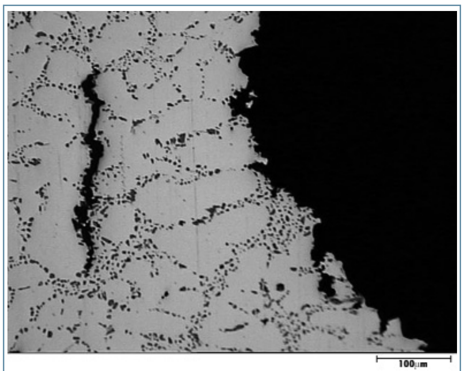


Fig. 7: Optical micrograph of the fracture profile: presence of a secondary crack.

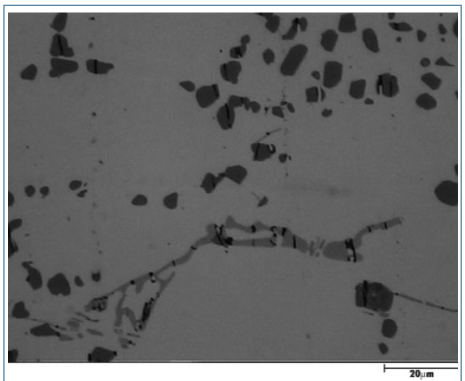


Fig. 8: Optical micrograph of cracked silicon particles and secondary phases.

SEM analysis of the fracture surfaces

As shown in Fig. 9, SEM analysis of the fracture surfaces of samples, taken from both types of casting, reveals a transcrystalline fracture [15]. This kind of fracture surface is typical of modified aluminum-silicon alloys subjected to T6 heat treatment. Visible traces of microdeformations (dimples) in the α-Al solid solution can be seen (Fig.10). In Fig. 11 the fracture surface reveals that dimples have been formed around cracked silicon particles, as a result of plastic deformation of the matrix. Fractures in the two-phase region with decohesion on the interface between α-Al and silicon particles have been found.

In Fig. 12 the presence of shrinkage porosity on the fracture surface is shown. The path of the crack is interdendritic, i.e. the fracture profile follows the interdendritic eutectic zone. Gas porosities have also been observed; the addition of either sodium or strontium for the modification of the alloy could increase the hydrogen content and, as a result, the presence of gas porosities [16].

On the fracture surface and in particular inside the shrinkage porosities, the presence of secondary-phase precipitates has been observed. Both β-(AlFeSi) and Al(Mg,Fe)Si intermetallic phases have been revealed by EDS microprobe [14, 15]. In Fig. 13 the SEM micrograph of a $Al_8Mg_3FeSi_6$ platelet with its EDS spectrum is reported.

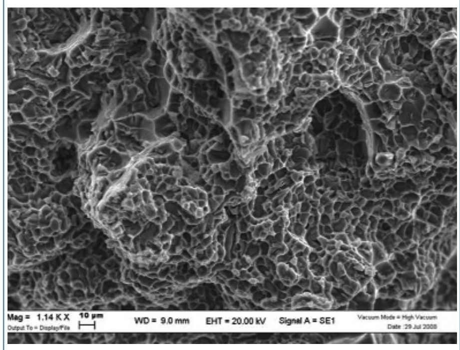


Fig. 9: Transcrystalline and ductile fracture.

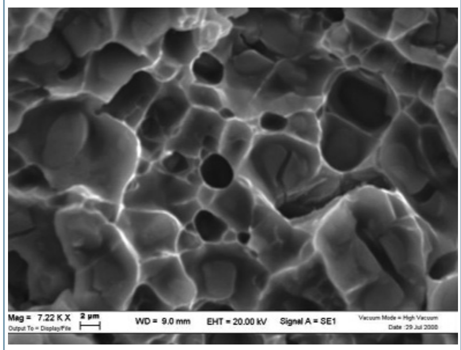


Fig. 10: Microdeformations in the α-Al solid solution.

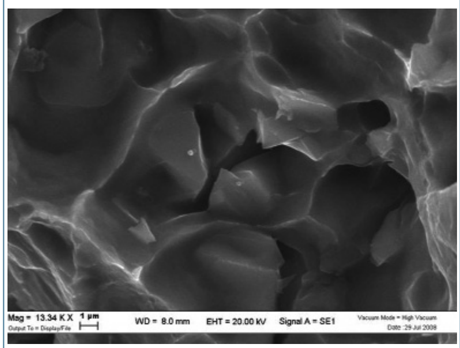


Fig. 11: Presence of a cracked silicon particle.

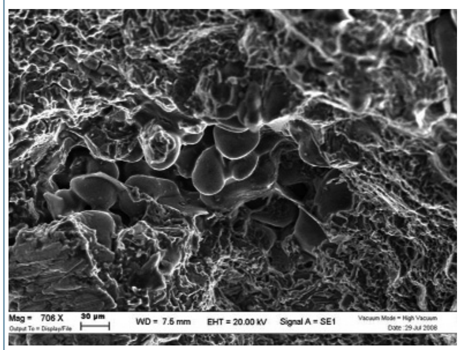


Fig. 12: Shrinkage porosity and the interdendritic path of the crack.

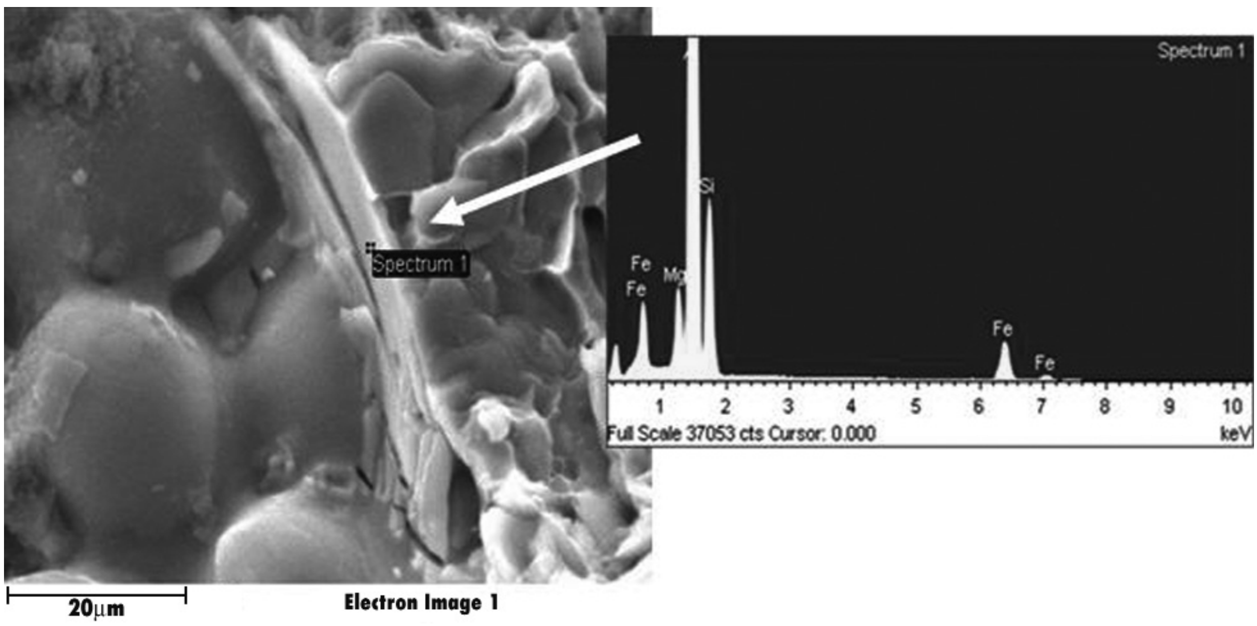


Fig. 13: $Al_8Mg_3FeSi_6$ platelet with its EDS spectrum.

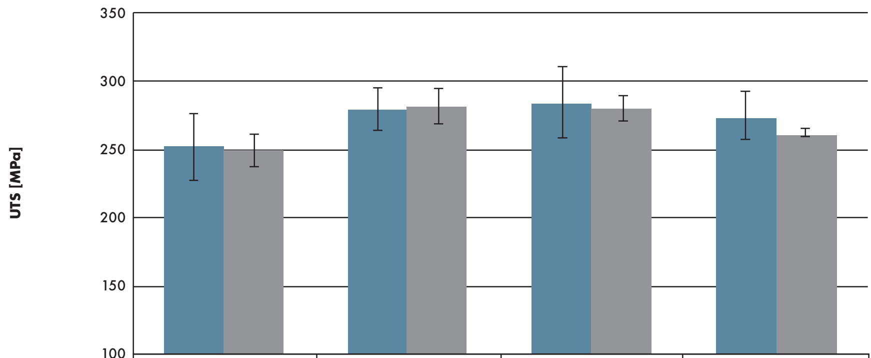
TENSILE TESTING RESULTS

From tensile tests, stress-strain curves have been obtained by attaching a knife-edge extensometer to the gage length. In Fig. 14 and Fig. 15 the mean values of UTS and of YS are shown, which have been obtained from the samples drawn in the four different positions. The standard deviations are reported as error bars. UTSs in position 2 and position 3 show the highest values, but in all the four regions values are acceptable according to the expected range of values. Regardless of the drawing position, the samples machined from the castings obtained by empty cores (E_{xy}-samples) show higher YSs than the ones obtained by full cores (F_{xy}-samples).

Notwithstanding, the maximum standard deviations of F_{xy}-samples are higher with respect to standard deviations of E_{xy}-samples.

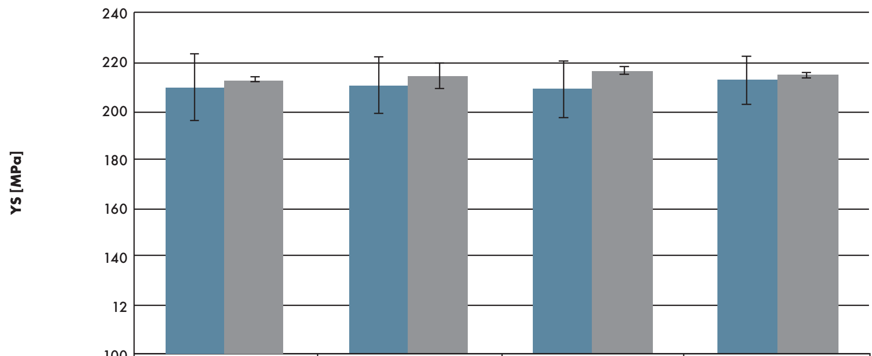
In Fig. 16 the mean values of A% calculated on all samples are reported. The standard deviations are very high and only the castings obtained by means of full cores are within the project specifications. The lowest values in E_{xy}-samples are probably due to the elimination of the hot flogging phase in the production cycle. Castings realised by means of empty cores most likely need improvement in the heat treatment parameters, in order to increase ductility.

Despite this lower A% in E_{xy}-samples, from data obtained from tensile tests, it is possible to conclude that the mechanical properties are comparable between the two different kinds of casting. Also, microstructural analysis has confirmed the main results obtained from mechanical tests. The ductility of the alloy strongly depends on the size, morphology and distribution of eutectic silicon particles. In E_{xy}-samples drawn from position 1 and 4, silicon particle distribution is less uniform than in the other positions, and this confirms the lower mean values of A%.



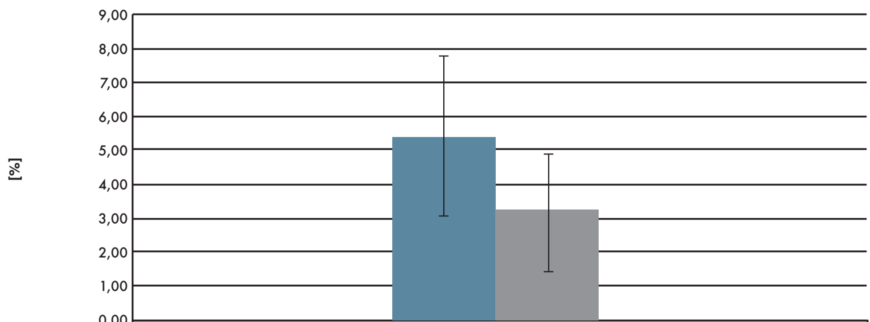
	Position 1	Position 2	Position 3	Position 4
Full cores	252,37	279,61	284,54	275,13
Empty cores	249,50	282,39	280,70	262,47

Fig. 14: Mean values of UTSs. The standard deviations are reported as error bars.



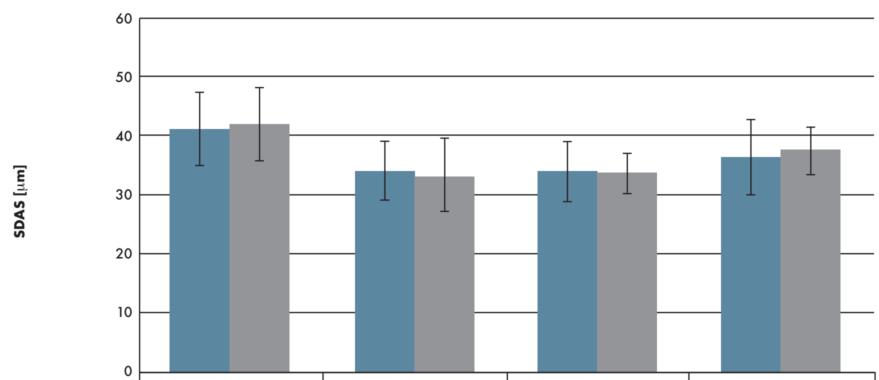
	Position 1	Position 2	Position 3	Position 4
Full cores	210,55	211,41	209,81	213,45
Empty cores	213,93	215,35	217,32	215,79

Fig. 15: Mean values of YSs. The standard deviations are reported as error bars.



	A%
Full cores	5,43
Empty cores	3,25

Fig. 16: Mean values of A%. The standard deviations are reported as error bars.



	Position 1	Position 2	Position 3	Position 4
Full cores	41	34	34	36
Empty cores	42	34	34	38

Fig. 17: Comparison of SDAS mean values in Fxy-samples and Exy-samples. The standard deviations are reported as error bars.

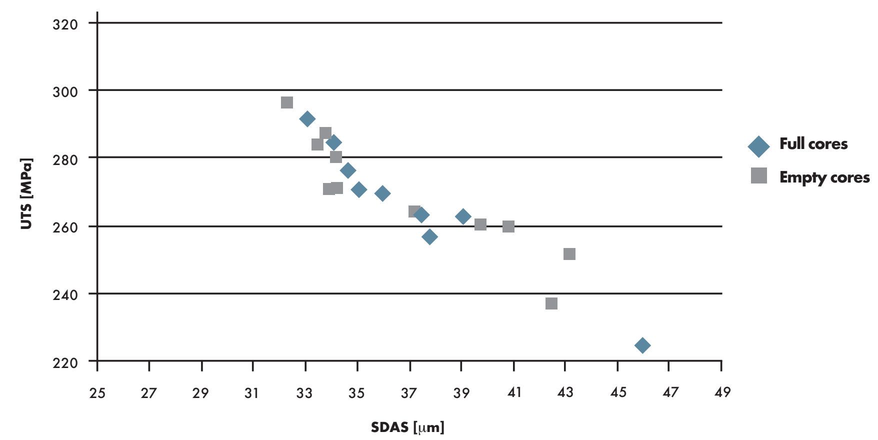


Fig. 18: Correlation between SDAS and UTS values.

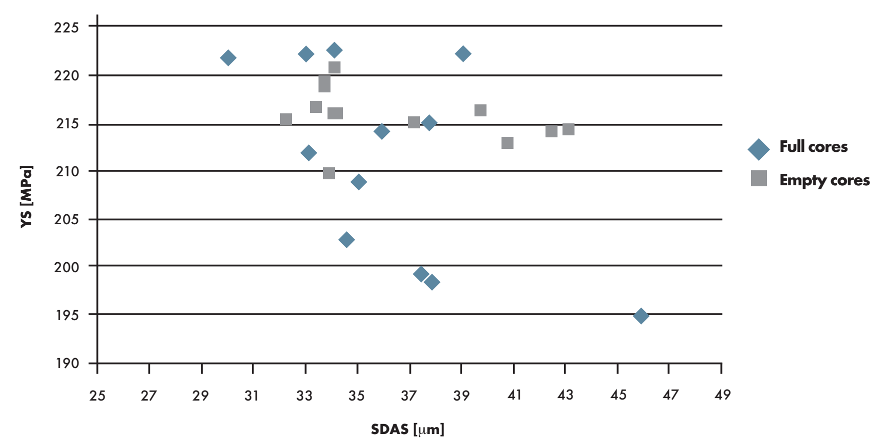


Fig. 19: Correlation between SDAS and YS values.

Relationship between tensile properties and SDAS

In Fig. 17 the SDAS mean values measured on F_{xy}-samples and E_{xy}-samples in the four different positions, are reported; as shown in the diagram, position 1 and 4 present the highest values and no significant differences among F_{xy}-samples and E_{xy}-samples SDAS values can be found in the different positions.
The tensile properties of each sample, in particular UTS and YS, are plotted in Fig. 18 and Fig. 19 as a function of SDAS. SDAS measurements are correlated to tensile strengths with the aim of investigating the microstructural effect on mechanical properties. The results show that an inverse correlation between UTS and SDAS can be found for both F_{xy}-samples and E_{xy}-samples; a finer microstructure corresponds to a higher UTS. Unlike UTS, YS does not significantly depend on the scale of dendritic structure [6].

TAIKAI ANALYSIS

By means of Taikai methodology, the analysis of the potential advantages of substituting full cores with empty cores in the production cycle, has been carried out. In this analysis the reduction of weights, costs and time-cycle in the different phases of the production cycle with empty cores, with respect to the production cycle with full cores, has been evaluated. All this information is summarised in Fig. 20 and considerable advantages of using empty cores in the production cycle of the rear-frame component can be seen. In particular, the elimination of the hot flogging phase because of the use of empty cores determines a remarkable reduction in production costs. In Fig. 21 the total production costs have been compared; by means of Taikai methodology, a reduction of 9% in costs has been found when using the empty cores instead of using the more traditional full cores.

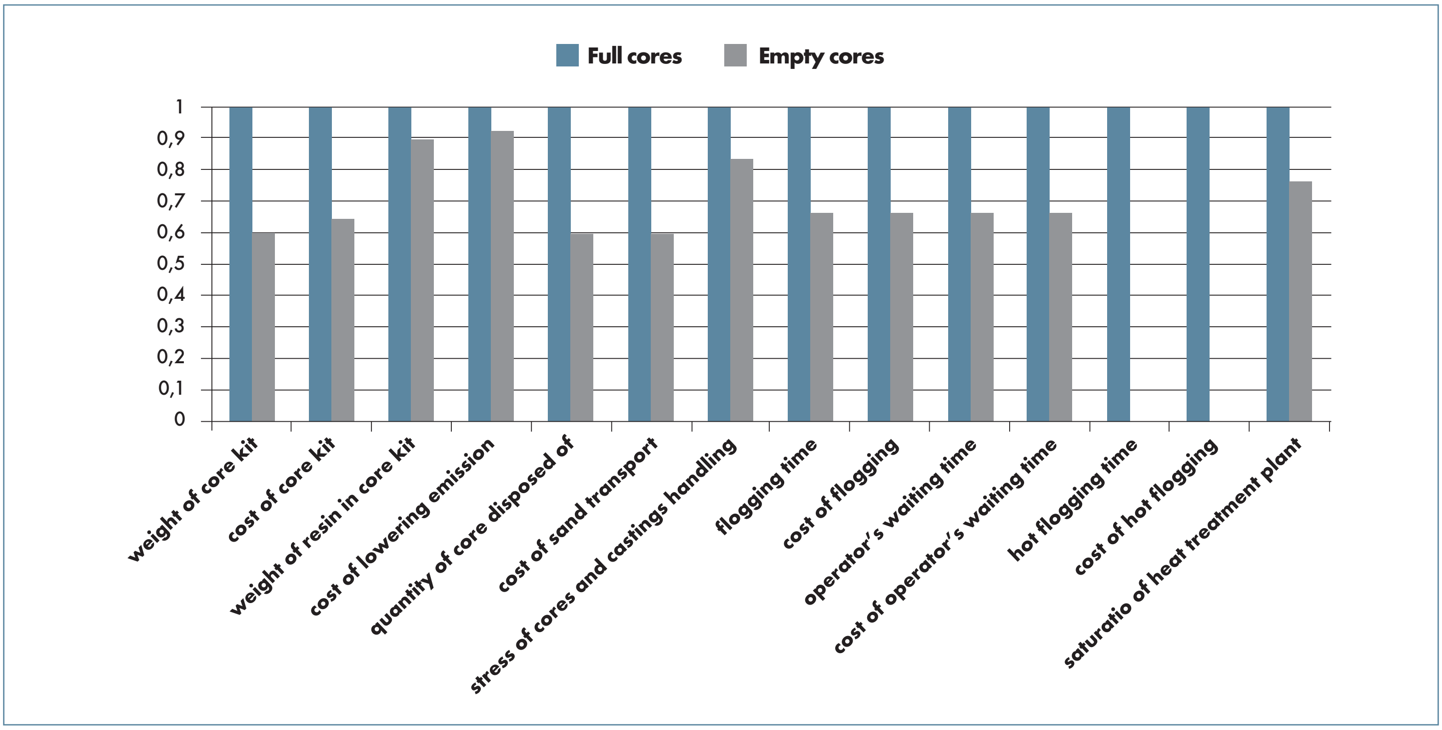


Fig. 20: Comparison of weights, times and costs of production with empty and full cores: normalised values.

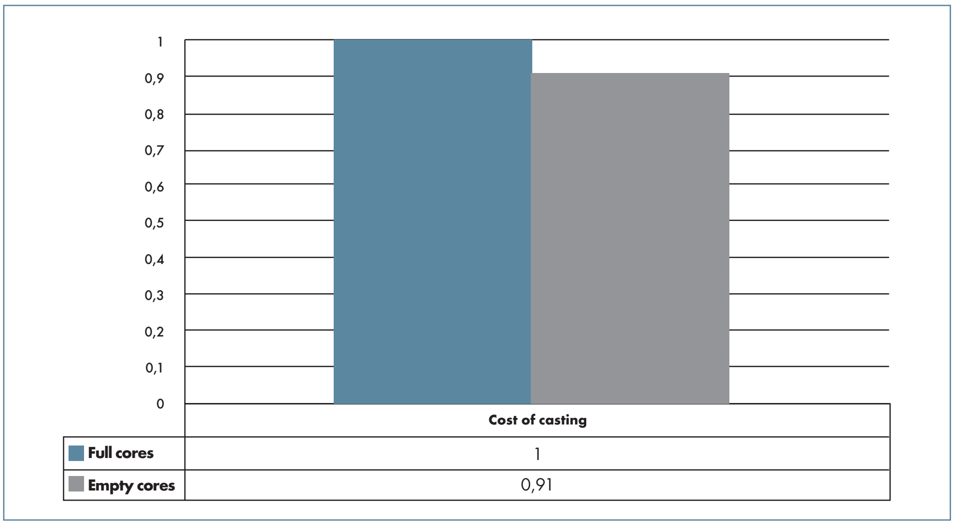


Fig. 21: Comparison of production costs with empty and full cores: normalised values.

CONCLUDING REMARKS

The following conclusions can be obtained from the analysis of microstructure and mechanical properties of the castings, realised with full and empty cores:

- Secondary dendrite arm spacing is comparable in corresponding positions for the two kinds of castings. The distribution of eutectic silicon particles is generally uniform and globular.
- On average, UTSs and YSs are inside the expected range of values; A%s should be increased in the castings realised with empty cores, probably by means of an optimisation of the heat treatment parameters. In general the mechanical properties of both kinds of castings are comparable.
- An inverse correlation between UTS and SDAS is obtained; a finer microstructure always corresponds to higher UTSs. YS does not seem to be well correlated to the scale of the dendritic structure.
- The crack crosses the interdendritic eutectic region: cracked eutectic silicon particles and microshrinkage and gas porosities can be seen on the fracture surfaces. Also brittle intermetallic particles are identified by means of EDS analysis.

The results obtained by using the Taikai methodology reveal that several advantages from the use of empty cores instead of full cores can be obtained. In particular, a reduction in the weight of cores determines lower handling costs, lower emission costs and a lower quantity of sand to dispose of. Moreover, the hot flogging treatment is not necessary to guarantee the required mechanical and microstructural properties and can be eliminated. Altogether, a reduction of 9% in the total production costs is evaluated.

ACKNOWLEDGMENTS

Many thanks are due to TFC-Galileo in Vaccolino of Lagosanto (Ferrara – Italy), for active cooperation and for supplying aluminum castings and X-ray equipment. The authors also express their gratitude to Dr. Stefano Succi for his experimental contribution to this research.

REFERENCES

[1] Apelian, D., Shivkumar, S., and G. Sigworth. Fundamental aspects of heat treatment of cast Al-Si-Mg alloys. AFS Trans., 97 (1989), 727-742.

[2] Shan, Z., and A.M. Gokhale. Micromechanics of complex three-dimensional microstructures. Acta Mater., 49 (2001), 2001-2015.

[3] Merlin, M., and al. Impact behavior of A356 alloy for low pressure die casting automotive wheels, Journal of Material Processing technology, 209 (2009), 1060-1073.

[4] Flemings, M.C. Solidification Processing, In McGraw-Hill (Ed.), New York, (1974).

[5] Spear, R.E., and G.R. Gardner. Dendrite cell size. AFS Trans., 71 (1963), 209-215.

[6] Wang, Q.C.. Microstructural effects on the tensile and fracture behavior of aluminum casting alloys. Metallurgical and Materials Transaction A, 34A (2003), 2887-289.

[7] Couture, A.. Iron in aluminum casting alloys – A literature survey. AFS Int. Cast Met. J., 6 (1981), 9-17.

[8] Càceres, C.H., Davidson, C.J., Griffiths, J.R., and Q.C. Wang. The effect of Mg on the microstructure and mechanical behavior of Al-Si-Mg casting alloys. Metall. Mater. Trans. A, 30A (1999), 2611-2618.

[9] Paray, F., Kulunk, B., and J.E. Gruzleski. Impact properties of Al-Si foundry alloys. Int. J. Cast Met. Res., 13 (2000), 17-37.

[10] Zhang, D.L., Zheng, L.H., and D.H. St John. Effect of a short solution treatment time on microstructure and mechanical properties of modified Al–7 wt.% Si–0.3 wt.% Mg alloy. J. Light Met., 2 (2002), 27-36.

[11] Pedersen, L.. Solution heat treatment of AlSiMg foundry alloys, PhD thesis, Norwegian University of Science and Technology (NTNU), Trondheim, (1999).

[12] Brown, R.. Foseco non-Ferrous foundryman's handbook. In Butterworth-Heinemann (Ed), Aluminium casting alloys, Oxford, (1999), 23-45.

[13] Salem S., Sjogren, T., and I.L. Svensson. Variations in microstructure and mechanical properties of cast aluminum EN AC 43100 alloy. Metallurgical Science and Technology, 25 N.1 (2007), 12-22.

[14] Backerud, L. and al.. Solidification characteristics of aluminum alloys. Volume 2: Foundry alloys. In AFS/SKANALUMINIUM (Ed), (1990).

[15] Warmuzek, M.. Aluminium-Silicon Casting Alloys: Atlas of Microfractographs, In ASM International (Ed), (2004).

[16] Gruzleski, J.E., and B.M. Closset. The treatment of liquid aluminum-silicon alloys. In American Foundrymen's Society Inc. (Ed), Modification and porosity, Des Plaines, Illinois, (1990), 57-73.