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Development, fashion, quality and innovations from SSM to rheocasting processes

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ABSTRACT

Purpose: Of this paper is to give an overview concerning some alternative methods for the production of enhanced performance light alloys components for critical industrial applications and to present an analysis of a new rheocasting process suitable fpr the manufacturing of high performance industrial components.

Design/methodology/approach: Innovative design of some automotive parts, their characterization throught radiographic analysis to verify the integrity of the samples from metallurgical point of view. OM and SEM microstructural characterization, optical microscope, mechanical characterization based on samples machined from the produced parts.

Findings: Semi-solid metal (SSM) processes demonstrated their capability to reduce the existing gap between casting and forging and during such a processes there are the opportunity to better control the defect level.

Research limitations/implications: The produced parts possess excellent properties, some criticises are related to the use of ceramic cores. There is the need of innovation in industrial design to open the mentalities to new advantageous solutions.

Practical implications: The principal goal to improve the competitiveness and energy savings associated to the production in high performance cars was fully accomplished.

Originality/value: A study on the feasibility was included opening the route for prototype production characterized by an adequate strength as well as by higher esthetical appearance than the element produced by gravity casting process. The presence of the defects does not negatively influence or compromise the employment of the callipers neither in extreme condition, favouring their use on a very high performance cars. In the future, extension of the proposed process for the production of other important applications are expected.

Keywords: Aluminium alloys; Rheocasting; Microstructure; Mechanical performances; Automotive parts; Quality assessment

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MATERIALS

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1. Introduction

Al-based alloys have an excellent combination of castability and mechanical properties, combined to brilliant corrosion resistance and good weldability. Looking in general terms to travel and mobility vehicles, replacing traditional Fe-based alloy with lighter alloys, some of the problems correlated to the fuel consumption and weight reduction are partially solved.

Generally, during solidification, in traditional manufacturing process, volume contraction is observed. This is due to the wrong feeding system and/or gas development, as also illustrated previously, which in turn generate some voids or cavities within a casting, which are further responsible for the presence of defects in the casting components. Commonly, interdendritic shrinkage pores, inclusions, secondary dendrite arm spacing are privileged crack initiation sites, independently of the loading conditions. These parameters affect the alloy mechanical performances leading to reduced strength and ductile properties, irregular crack development and in extreme conditions can cause the materials failure.

The continuous increase of use of Al-based alloys in different applications requires producing high integrity and enhanced performance parts. For such reason the research community in cooperation with manufacturing industries are focusing high attention toward new products employing innovative materials and procedures. Forging clearly is always the best method but at the same time it is also the most expensive one.

1.1. Thixo and rheo processes

The new trend is to obtain performances comparable to those obtained by conventional techniques, but in a cheaper way. New and recently developed semi-solid metal processing are able to attain higher level of properties and performances. Moreover, the real and important advantages of the semi-solid metal processing, related to the faster production rates at lower costs, represents a possible solution versus conventional methods. Energy savings characteristics of the processes together with the reliability, safety and high performance components make these techniques very attractive for industrial mass production [1-10].

Semi-solid processes can reduce the existing gap between casting and forging and during such a process the possibility to better control the defect level can be attained. Using these processes, significant reduction of the defects was obtained, as well as good surface quality and high dimensional accuracy [11-13]. One of the central issue of the development process is represented by the technological transfer from research labs to industry for affordable mass production. A new rheocasting process suitable for the manufacturing of high performance industrial components is presented in [14,15], where a method is described for controlling the process route as technological parameter regards.

1.2. Recent development on semi solid metal processing

Semi-Solid Metal (SSM) processing has been extensively employed through the world, mostly, for military, aerospace, automotive and marine applications for manufacturing high quality components. In Europe, engine groups, suspension level arms, fuel rails for automobiles have been prevalently developed. During the last decades under the enthusiastic and competent guidance of Mr Chiarmetta SSM processes attained in Italy at Stampal Spa (Torino) an unquestionable high level of industrial development with the production of large numbers of high performance automotive parts, like variety of suspension support, engine suspension mounts, steering knuckle, front suspension wheel, arm and rear axle [14-19]. Some of them are illustrated in Figs 1 to 4, with the indication of the used alloy and of the heat treatment state. It is interesting to observe in Fig. 2 the presence of welding also, to form a very large and important part; it is evident that all the exposed parts must be really very performing and safe.

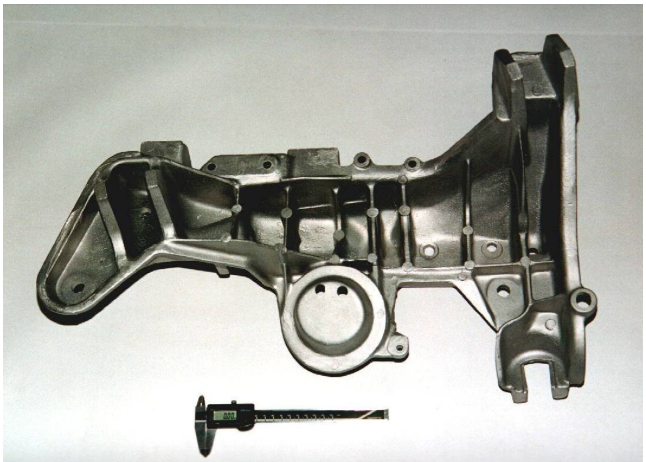

Fig. 1. Suspension support A357 T5 (Mr Chiarmetta, STAMPAL SpA)

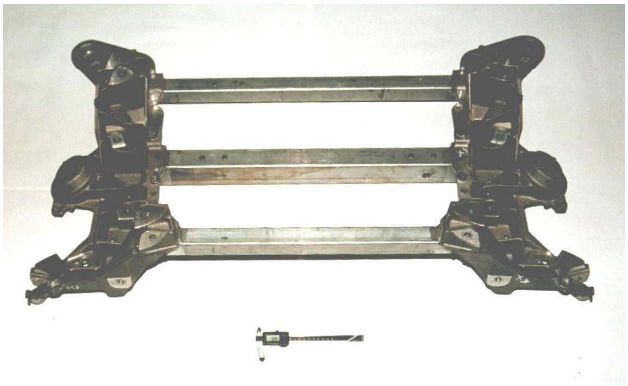

Fig. 2. Suspension support assembled A357 welded with 6061 struts, T5 and T6 (Mr Chiarmetta, STAMPAL SpA)

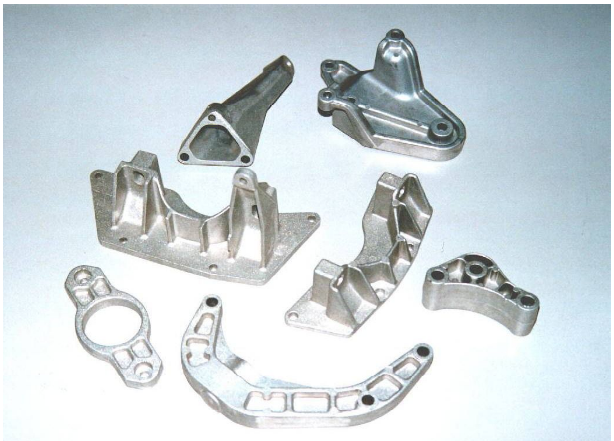

Fig. 3. Engine suspension mounts A357 T5 (Mr Chiarmetta, STAMPAL SpA)

Fig. 4. Wheel A357 T5 and front suspension arm A356 T6 (Mr Chiarmetta, STAMPAL SpA)

During the last few years, an increasing tendency in applying the rheocasting route, from both research centres and industries, have been observed. Using a molten alloy as a starting material, allows eliminating the necessity for specially prepared feedstock materials, thus reducing the overall cost of the process and giving the way to an easier realization compared to a two step process. Several Rheocasting technologies have been developed and are being commercialized worldwide: New Rheocasting Process (NRC^{TM}), Sub-liquidus Casting (SLC^{TM}), Slurry on Demand (SoD), Honda process, New Semi-Solid Casting-Hitachi, Rheo-Die Casting process (RDC), Continuous rheoconversion process (CRP), Swirl enthalpy equilibration device (SEED), RheoMetal process, Semi-Solid Rheocasting (Idra Presse SSR^{TM}), etc.

Sub-Liquidus Casting is a semi-solid casting technique has been developed in 2001 in the USA and presents improved overall quality than traditional casting methods. The products obtained show reduced porosity and less contraction with the opportunity of applying heat treatments. During the sub-liquidus casting, the pre-grain-refined material is poured into the shot sleeve at temperatures just above liquidus and cooled to a semi-solid state before transfer into the die [20-22].

Slurry-on-demand, as a new SSM process, is similar to die-casting in terms of cost, thanks to the possibility to introduce ceramic particles to molten Al with complete wetting and no clumping of the particles. This process avoids the step of producing and reheating the special thixotropic billets.

Swirl Enthalpy Equilibration Device process, patented by Rio Tinto Alcan in collaboration with the National Research Council Canada is a liquid based method and has the advantage of producing a semi-solid mixture at a lower cost than other existing semi-solid casting processes. The swirl enthalpy equilibration device consists of extracting a controlled quantity of enthalpy to produce the slurry and then draining away the excess liquid to form a compact slug ready for casting. Employing this technology a lower manufacturing cycle time occurs, consequently raising productivity. Such a process is industrialized with fully automatic machine retrofitted to both horizontal and vertical high pressure.

When, years ago, Mr Gianluigi Chiarmetta leaved Stampal, he never stopped his activity and looking to continuous innovation he strongly contributed to the development of a modern Rheocasting process, to produce of novel and very competitive components [14,15]. This innovative rheocasting process “ATS”, has been developed in the recent years at the ATS Srl Company in Lugo (RA), Italy. An important aspect of the developed process is related to the possibility to obtain quite wide range of thicknesses, starting from about 2 mm.

The process runs by means of a TCS vertical hydraulic press Rotorone 400 tons model; the press has an injection piston of 180 mm diameter; the closure power corresponds to 400 tons with an injection power of 320 tons. In the ladle furnace, the liquid metal is waiting, in argon atmosphere, to be collected.

The process is a three step one: under the inferior level of the press, a turning table moves with the containers set up at 120°C: in the first one there is the slurry which will be injected after rotation; in the second one there is the evacuation of the biscuit; the third one is lubricated waiting from the ladle new quantity of slurry to inject. The two upper and lower half dies are heat controlled by oleo-dynamic control panels. When the requested injection temperature is reached (between 577°C and 590°C, depending by the employed alloy), the piston pushes the slurry very slowly through the ingrate until the filling of the cavity is completed. After a very short time, aiming to maintain the pressure so that the cycle could finish, the piston goes down carrying the biscuit and by consequence cutting off the ingrate piece. When the press opens, the upper part lifts allowing the piece to exit, which is facilitated by an ejector. The cycle is ready to continue after lubrication of the die.

Thanks to the superior properties, quality and reliability demonstrated by this innovative rheocasting process [23], developments gone on and in this paper a particular attention will be dedicated to assess the effects caused by T6 heat treatments on A356 and A357 alloys after rheocasting production and to the presentation of some results obtained using the ATS very promising technique for two series of components, namely a space frame in A356 alloy and brake callipers for sport car, using A357 alloy. The obtained results are here presented and discussed.

2. Description of the approach, work methodology, materials and experiments

In Table 1 is indicated the average chemical composition of the employed alloys A356 and A357, as it is evident the main difference between the two alloys is the magnesium content, higher in 357 grades to improve the alloy strength.

2.1. Assessments of T6 heat treatment

The purpose of this section is the evaluation of the mechanical and the fatigue behaviour of the SSM A356 and A357 aluminium alloys, rheocast and T6 heat treated, and the correlation of the results with the microstructures of the component [19]. The analysis has been carried out on a suspension arm injected in a rheocasting 800 tons plant in Stampal S.p.A. After a preliminary tensile test analysis, axial high frequency fatigue tests have been carried out at room temperature on specimen cut out from the suspension arm to determine the Wöhler curve and the number of cycles to failure. The results of this work allow to assess the effects of T6 heat treatment on Semi-Solid components for industrial applications in the automotive field.

In Fig. 5 the typical microstructure of the A357 semi-solid slurry is shown; at higher magnification it is possible to individuate the phases in the as cast state: α-Al, Mg_2Si, eutectic silicium and, in same rare cases, α(AlFeSi), α(AlFeMnSi). Micrographic analysis on different sections of the formed component, especially in the point where the design is more complex, highlights that microstructure has a good homogeneity, as shown in Fig. 6 for the two alloys A356 and A357, both T6 state; moreover after heat treatment no acicular or polygonal phases have been found. The absence of these kind of phases improves the fatigue strength, reducing the point of fracture initiation. The same figure allows the following considerations on the morphology of the eutectic silicium: it is rounded, consequently to the T6 treatment, either for the A357 alloy, modified with strontium, or for A356 alloy, not modified. Any significant difference can be detected between the two alloys after heat treatment. The low content of defect, also in the more complex sections, is another point to be outlined and is one of the advantages of rheocasting process, comparing with other casting processes.

Tensile tests have been carried out on specimens, cut off from the suspension arms, following DIN 50125 standard. Table 2 reports the average values of the static mechanical properties for both the compositions, for both the alloys, in terms of ultimate and yield strength as a function of elongation. Value of the standard deviation confirms the low dispersion of properties for this type of SSM process.

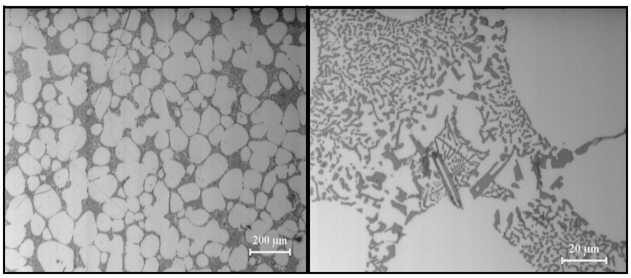

Fig. 5. Microstructure of the A357 semi-solid slurry at 580°C

Table 1.
Chemical composition (wt. %) of the A357 and A356 used alloys

Elem.	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
A357	7.05	0.1	0.05	0.1	0.70	0.07	0.25	b.
A356	6.95	0.15	0.01	0.02	0.34	0.01	0.07	b.

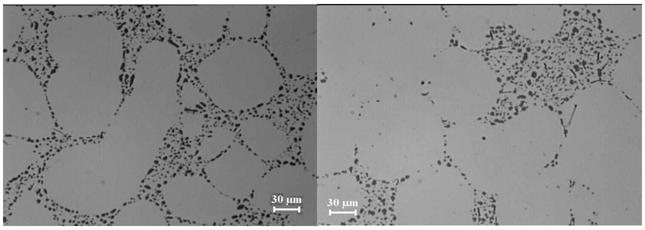

Fig. 6. Microstructure of rheocast suspension arm, T6 state, A356 (left) and A 357 (right)

Table 2.
Tensile properties for A356 T6 and A357 T6 samples machined from suspension arm

Alloy	A 356 T6	A 357 T6
$\sigma_{0.2}$ [MPa]	229	302
UTS [MPa]	299	350
Elongation %	12	5.4

The specimens, with rectangular cross section, used for fatigue tests have been machined from components following the ASTM E 466-82 standard. Constant amplitude axial fatigue tests have been performed at high frequency in a RUMUL test machine, with a stress ratio R = -1, in air at room temperature. The fatigue tests, for both the alloys in T6 state, leads to the determination of the Wöhler diagrams, reported in Fig. 7; fatigue limits are calculated according to the stair case method. The fatigue limits obtained are: 120.71 MPa for A357 T6 alloy and 109.29 MPa for A356 T6, with a probability of surviving of 50% of specimens after 10^7 cycles.

Fractographic analysis on a SEM microscope of the fracture surfaces of specimens after failure, highlights the absence of defects directly connected to the fracture initiation; particularly any detrimental casting defect, such as gas porosity or shrinkage cavity, has been detected.

The comparison of the fatigue strength (Fig. 8) has been made for the A356 T6 alloy formed with different technologies and tested in the same conditions. With the rheocasting process it is possible to reach a fatigue strength significantly higher compared with the traditional casting processes; this value is comparable only with that of the gravity casting followed by the LHIP process (Liquid Hot Isostatic Pressing), a special treatment applied on cast parts, in order to reduce the internal defects and to increase the mechanical properties that is, up to now, used only for niche and high performance demanding market.

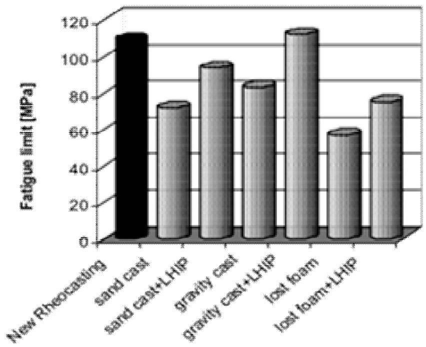

Fig. 8. Comparison of fatigue limits for A356 T6 alloy after different casting processes

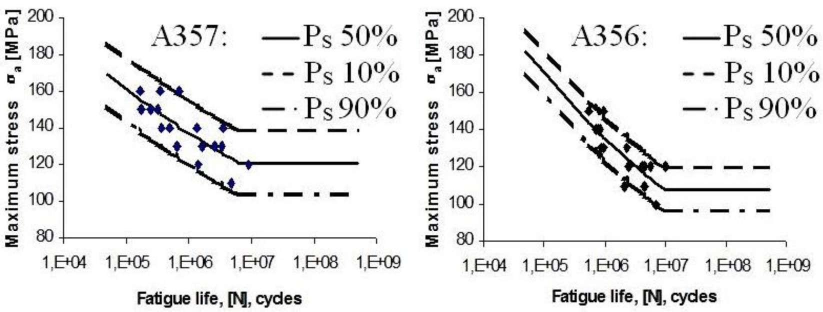

Fig. 7. Wöhler diagrams for rheocast A356 T6 and A357 T6 components

2.2. Production of the space frame

The space frame is characterized by a quite complex shape (Fig. 9) having 2 mm maximum thickness and a length of about 300 mm and it has been realized using the well known A356 alloy, with low Fe content, maximum 0.08 wt%. T6 heat treatments have been performed, while the soundness of the parts has been certified by non-destructive tests. These parts are produced and mounted on a top level and famous sport car [15].

Fig. 9. The space frame produced with ATS process

Non-standard samples for mechanical tests have been machined directly from the components, as indicated in Fig. 10, where the zones suitable for the extraction of flat tensile test samples are highlighted. In the same figure the tensile properties measured on some machined samples are indicated.

Following the mechanical tests, SEM to observe some morphological details and to evaluate the influence of the process and of the alloy conditions on the fracture behaviour has carried out fracture surface analysis. On the polished transverse sections of the samples morphological analysis has been performed.

The second series of part that have been considered are brake callipers, in this case the A357 alloy has been used; moreover, due to the complex shape of the calliper, it is a hollow part with undercuts, the use of strong enough cores was necessary [24].

A significant constraint to be considered when designing High Pressure Die Casting (HPDC) components is related to the need of using steel cores which are required to withstand the forces generated by the high speed metal flow into the die cavity during the filling and the high pressures (800-1500 bar) applied on the liquid metal during the solidification of the casting.

Such kind of metallic core does not allow creating undercuts or complex shape cavities into the casting thus limiting the flexibility in the design of the geometry of the component.

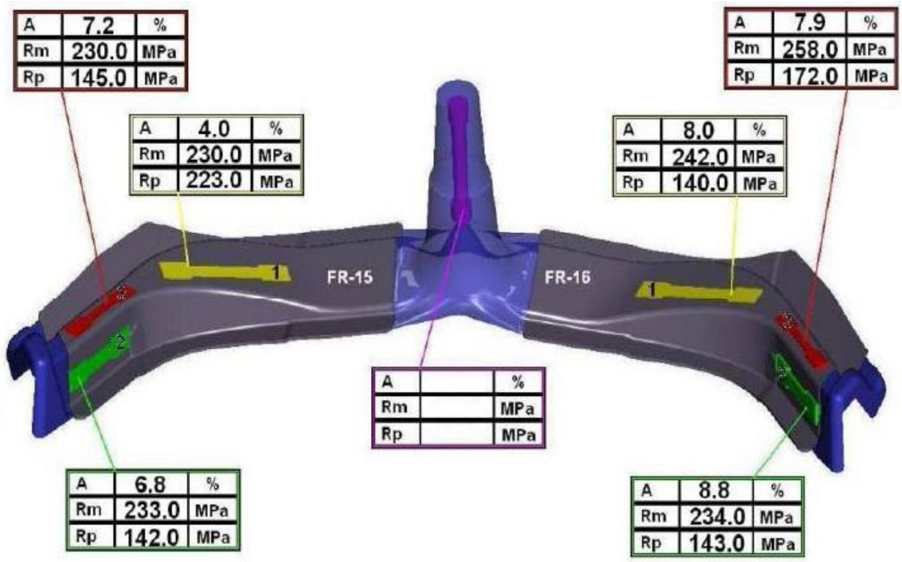

Fig. 10. Ingrate and feeding system to produce two space frames and the zones suitable to machine samples for tensile test

In the present application, ingate velocities are very low (< 1 m/s) but the high packing pressures (> 600 bar) and undercuts are incompatibles both with metal- and also with lost sand-cores. In fact, the bonding effect among the sand grains generated by organic or inorganic binders is relatively weak and the resulting mechanical properties of these conventional cores are relatively low, so they are not suitable for applications where overpressures are applied. Therefore, for the production of the calliper, special ceramic lost cores were adopted, able to reach enhanced mechanical properties, in particular in terms of stiffness, bending and compression strength, to withstand the stresses generated during the semi-solid casting process [25].

The present research has mainly focused on two important aspects:

1. on the performances of the cores in terms of structural behaviour, resistance against metal infiltration, deformation and removal;
2. on the quality of prototype callipers as regards soundness, microstructural features and suitability for heat treatment.

Ceramic cores have been employed which are prevalently influencing the appearance of the brake callipers. The hardening mechanism and the structural resistance of ceramic cores are mainly based upon a sintering process: in this way it is possible to obtain cores with a wide range of mechanical properties as a function of the sintering temperature, avoiding, in addition, the limits and problems coming from the conventional organic binders. In the sintering process the single particles of ceramic material are bonded together by diffusion, allowing to reach elevated values of the mechanical properties and modulus of elasticity, well over what is accessible with the use of conventional binders. Even more important, ceramic cores do not contain any kind of binders, i.e. release of gases during the casting process can be avoided.

To check the metallurgical integrity and to individuate and correct the parameters related to the injection step, radiographic analysis has been carried out on the produced components. Depending on the position of the investigated zone and due to the complex shape of the produced component, in some cases higher than 35 mm thickness had to be observed, making the radiographic analysis difficult.

To assess the quality of the callipers, radiographic analysis (RX, model) has been performed in parallel to the production process, both to verify the integrity of the samples from metallurgical point of view and to individuate and correct the parameters related to the injection step. Standard T6 heat treatment has been performed.

For the microstructural characterization, optical microscope has been employed, whilst to evaluate mechanical properties a lot of samples have been machined from the produced callipers, as illustrated in Fig. 11.

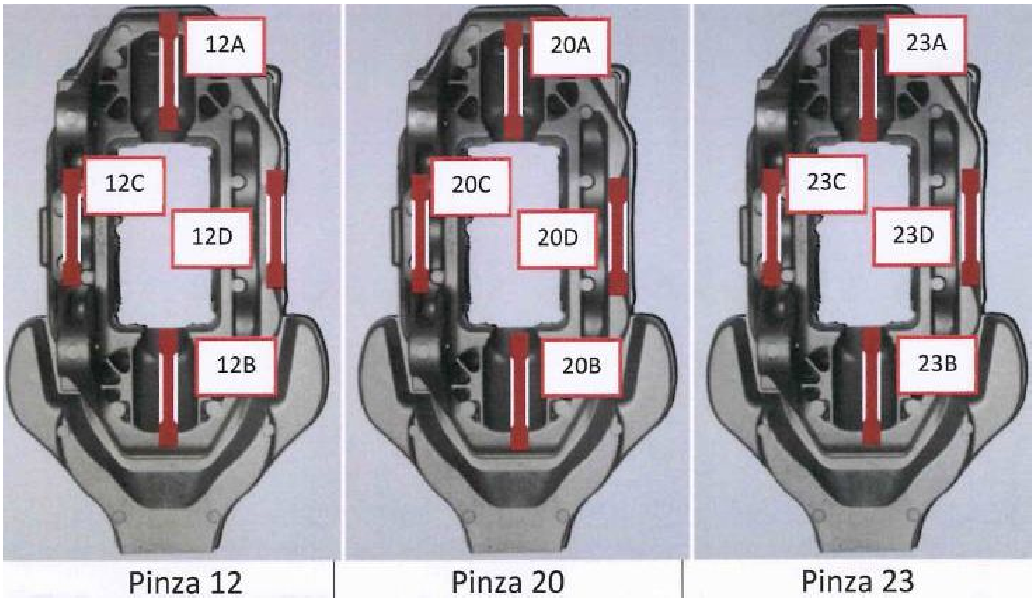

Fig. 11. Photograph of the produced brake calliper, with indication of the zones where tensile test samples have been machined

3. Description of achieved results

3.1. The space frame

In Fig. 6 some results obtained during first trials by tensile test performed on the samples machined from the space frame are already shown and it was also possible to obtain samples from the feeding system. In this way it is possible to define tensile properties for massive samples and for thin samples.

The average values of yield stress, ultimate tensile strength and % of elongation are listed in Table 3 and it is evident that massive samples show slightly lower values with respect to those of thinner part, where finer microstructure is expected. Anyway the differences between the values of the two zones are very small and indicates the very high performance and reliability of the process, the measured hardness was in the range of 90 HB.

The morphology of the fracture (Fig. 12) analysed by SEM highlighted the presence of small dimples to indicate a ductile behaviour of the alloy. As defects regards, occasionally the presence of some small size brittle particle has been detected, with no direct influence on the mechanical failure of the alloy.

The microstructure of the alloy as observed at the optical microscope is constituted by an homogeneous distribution of globules of aluminium solid solution surrounded by very fine Al-Si eutectic phase and the Si particles are small and well rounded, Fig. 13.

3.2. The brake calliper

Actually, the brake callipers has been manufactured by gravity casting method. Although the process remains a valid procedure from economic point of view and allows obtaining the final products in a relatively short time, as accuracy concerns, there is space for further development. Semi-solid production permits to develop also thin parts with very high precision, which is more difficult to realize using traditional processes. The most important benefit by using semi-solid method regards the achievement of an aesthetically pleasing component and this feature constitute a crucially important aspect in high performance car production. In addition, reduction of about 5% of the total weight has been achieved [24].

Table 3.
Average mechanical properties of samples machined from the brake callipers

Sample	Massive	Thin
$\sigma_{0.2}$ [MPa]	190	200
UTS [MPa]	260	280
Elongation %	6	7

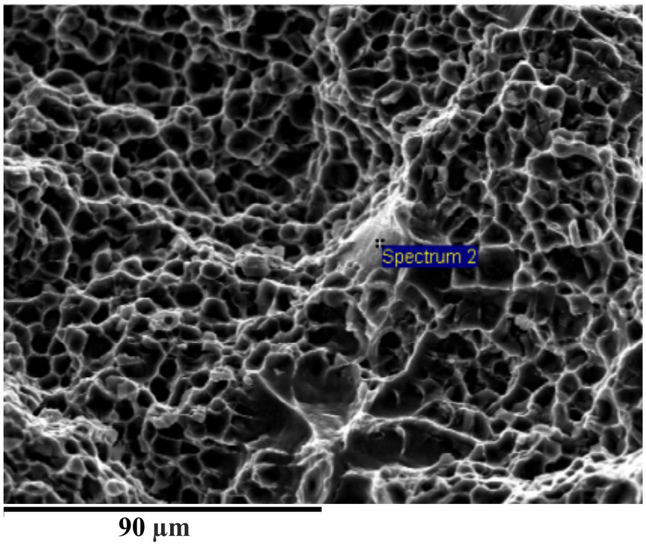

Fig. 12. Dimples as appearing on the fracture surface of A356 T6 space frame samples after tensile test

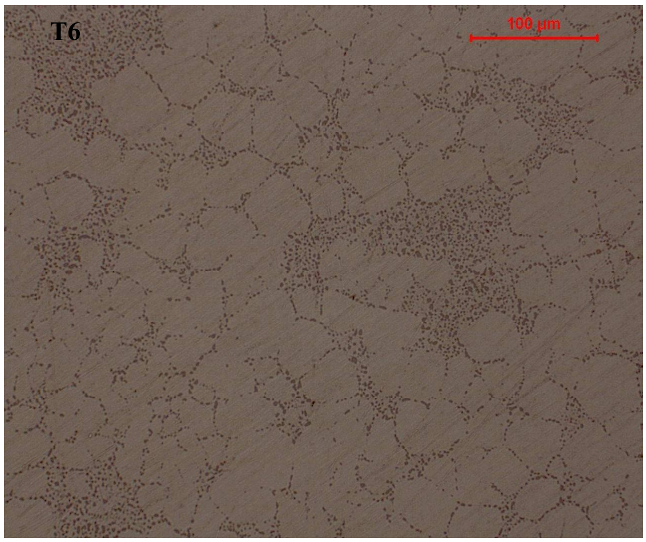

Fig. 13. Microstructure of A356 T6 alloy in space frame samples

The comparison to assess the differences between the traditional and the innovative manufacturing processes was completed by metallographic analysis. Fig. 14 reports the dendritic microstructure of the brake calliper produced by gravity casting process (a) and the globular and fine microstructure realized in the case of rheocasting process (b).

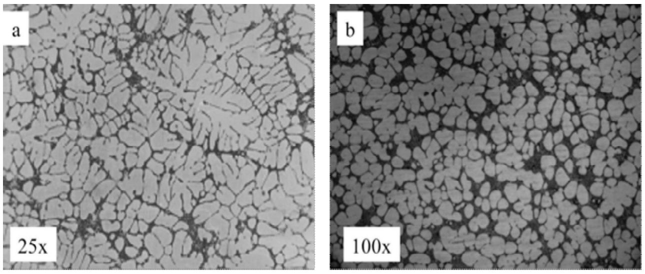

Fig. 14. Microstructure of the brake calliper produced by gravity casting process (a) and by rheocasting process (b)

Concerning the callipers produced trough the rheocasting process, the most critical parts, as defects concern, firstly evaluated by radiographic inspection and further confirmed by Finite Element Analysis (FEM) have been submitted to microstructural analysis too, after an adequate metallographic preparation. The microstructure of "worst case" castings reveals the presence of some defects. In particular a special type of defect has been observed in Fig. 15a: the surface oxide on the liquid is folded in to produce crack-like defects, known as "bi-films" [26-28]. These types of defects are extremely thin and the surface turbulence causing the entrainment of bi-films and associated bubbles can be developed as reported in Fig. 15b.

In addition to validation bench tests on sound pieces to X-ray screening, further severe braking cycles tests were performed also on pieces "worst case" to evaluate the behaviour of the component even in the presence of identified defects. The results were excellent: following a subsequent X-ray screening, the defects present on the pieces "worst case", previously identified and measured, were not propagated inside the pieces after $>10^6$ fatigue cycles with high pressure fluid inside. This demonstrated a high fracture toughness (in terms of stress intensity factor k_{IC}) and a resulting very high reliability of the component. On the basis of the results coming from the fatigue test, one can claim that the presence of the defects does not influence negatively and does not compromise in any way the performance of the callipers neither in extreme condition [24]. Certainly, the special globular microstructure seems to be more appropriate than the dendritic one to restrain crack propagations, eventually starting from the damaged areas.

Finally, static tensile test has been carried out on dissected specimens: Table 4 summarises the results and also reports the standard requirements (UNI EN 1706/2010) for the sand casted and chill casted A357 T6 heat treated alloy. The measured values exceed the thresholds indicated in the standard.

To assess the reliability of the samples, the damaged surfaces have been prepared adequately for severe industrial tests at high pressure (about 200 bar), as well as severe braking cycles. In particular, the standard requirements where a few of hundred thousand braking cycles are retained as minimum, the tested callipers reached over three time the minimum requested cycles without any damage. This behaviour has been observed even in the case of defected samples.

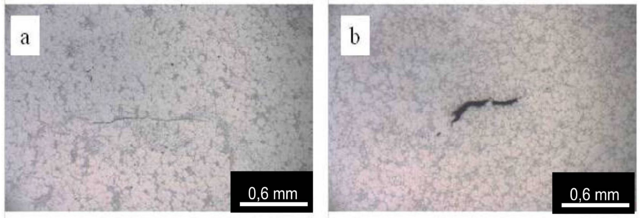

Fig. 15. Microctructures of scraps showing the presence of some defects, like bi-films

Table 4.
Average tensile properties of the rheocast samples, *sand casting values reported in UNI EN 1706/2010, **chill casting values reported in UNI EN 1706/2010

Samples	UTS (MPa)	Yeld Strength (MPa)	Elongation (%)
A357 T6 heat treated	340 ± 14 *250-**320	302 ± 4 *210-**240	4.135 ± 2.7 (*1) (**3)

4. Conclusions

In this paper some components for automotive application in A356 and A357 alloys produced by rheocasting processes have been considered. The effect of T6 heat treatment on mechanical and fatigue properties was previously assessed. A complete analysis of the rheocasting process, applied to a suspension arm formed with the alloys A356 and A357, lead to a satisfactory evaluation of this innovative process. The microstructure evaluation highlights the rounded morphology of the α-Al grain, necessary to join the optimum rheological behaviour in the semisolid state. The low content of internal defects, associated to a rounded morphology of the eutectic silicium after T6, justify the very good mechanical properties. Rheocasting is suitable for the production of structural, safety components, and can find large applications in the automotive market.

Following on going research activities some steps concerning the optimization of a new rheocasting process have been considered and presented for production of automotive components for high performance cars: a space frame component and a new generation of brake callipers. The main goal to improve competitiveness and energy savings associated to the production in high performance cars was fully accomplished. Implementation of rheocasting route in the case of brake callipers was realized by using special ceramic cores in the manufacturing process. The research considered also the performances of the cores in terms of structural behaviour, resistance against metal infiltration, deformation and removal and on the quality of the prototype callipers as far as regards soundness, microstructural features and suitability for heat treatment. A study on the feasibility was included opening the route for prototype production characterized by an adequate strength as well as by higher esthetical appearance than the element produced by gravity casting process. The presence of the defects does not negatively influence or compromise the employment of the callipers neither in extreme condition, favouring their use on a very high performance car. In the future, extensions of the proposed process for the production of other important applications are expected.

Rheocasting process and the innovative ATS process, in particular, confirm again, with respect other casting processes, their capability to produce parts with better reliability, higher properties, and performances, definitely they are very competitive for many aspects.

Acknowledgements

The author acknowledge the co-authors of referenced papers, in particular my colleague Mme I. Peter for the collaboration to laboratory analyses, tests, evaluation and discussion, Mr I. Gattelli (ATS, Lugo) for the strong effort done to the development of the innovative process and the production of the studied components.

A special thank to Mr Gianluigi Chiarmetta, at the memory because with too early time we had to say goodbye (June 2015); he has been a distinctive presence in the S2P community and one who has contributed significantly in the development of the semi-solid processes. He was a kind gentleman appreciated for is energy and consequence to transfer the Semi-solid Process from research to industrial scale, he was really a referring and enterprising person, working hardly with passion, competence and availability: all the S2P community will certainly miss him.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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