Development of an Innovative Low Pressure Die Casting Process for Aluminum Powertrain and Structural Components**

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Abstract

An innovative Low Pressure Die Casting (LPDC) process has been developed for aluminum cast components based on the application of an extra pressure during the solidification process. The new process, named "Low Pressure Squeeze Casting" (LPSC) has been proved to be able to increase the solidification rate, refining the microstructure of the casting and reducing its shrinkage porosity. Furthermore, the cycle time is also reduced, increasing the productivity of the process. Two demonstrators from the automotive and wind power industries have been produced to validate the process in a relevant industrial environment.

1.- Introduction

Low Pressure Die Casting (LPDC) is one of the most widely used casting processes for manufacturing light-weight aluminum components in industrial sectors such as the automotive,[1] energy, electronics, etc. This process allows an excellent compromise between quality, costs, productivity and geometrical feasibility.

The principle of this process is quite simple: the steel die and the filling system are placed over a sealed furnace containing the molten metal. A refractory-liner riser tube extends from the bottom of the die into the molten metal. When a pressurized gas is introduced into the furnace the molten metal rises up to the tube to flow into a die cavity. Once the die cavity is filled, metal solidifies and the overpressure in the furnace is removed, allowing the remaining molten metal in the riser tube to fall back into the furnace.[2]

The low injection velocity and the relatively high cycle time lead to a good control of the fluid-dynamics of the process, permitting the air to escape through vents and the parting lines of the die and avoiding the defects originated by turbulence phenomena. The process is capable to produce castings with a relatively low amount of porosity. Good dimensional accuracy and surface finish can be obtained and sand cores can be used.[3] This process is competitive in comparison with other casting processes when small or medium series need to be produced (<10000 pcs/year) and/or when heat treatment is needed to improve the mechanical properties. However, for large series with less mechanical requirements and smaller wall thicknesses, high pressure die casting (HPDC) is more competitive.

With the objective of reducing the cycle time of the LPDC process, a squeeze sequence has been introduced in the process. This sequence is applied in the upper part of the mold during the solidification, thus decreasing the total aluminum solidification, mold opening and part extracting process time. Apart from cycle time reduction and production rate increment, the increase of the solidification rate leads to a refinement of the alloy dendritic structure and secondary phases.

During the squeeze sequence, the high applied pressure, several orders of magnitude greater than the melt pressure developed in normal casting processes, keeps entrapped gases in solution and squeezes molten metal from hot spots to incipient shrinkage pores. As a result, the porosity in a squeeze-cast component is almost eliminated.[4] Furthermore, due to the elimination of the air gap at the liquid-mold interface by the applied high pressure, the heat transfer across die surfaces is enhanced, increasing solidification and cooling rates.[5-7] Thus, fine microstructures with reduced porosity are achieved, obtaining superior mechanical properties castings.

In this paper, the potential of the new LPSC process to produce complex aluminum casting components with a higher production rate and better mechanical properties than those produced through conventional LPDC process will be analyzed. The technology validation in industrial relevant environment will be also carried out through the manufacturing of two demonstrators selected from automotive (cylinder head) and wind power (bell housing) sectors.

Internal combustion engine **cylinder heads** are facing a critical development point: the always increasing demands for efficiency and the compliance of new emissions regulations are pushing engine designers towards downsizing components which, in the specific case of cylinder heads, results in higher operation temperatures and pressures.[8] These conditions require considerable improvement of static and dynamic mechanical properties. To achieve this objective an innovative LPSC process has been proposed in this work.

Wind power sector is also looking to improve the efficiency of wind turbines, to decrease electricity generation cost and widespread the use of this kind of renewable energy. In this sense, the weight reduction of the turbine components and the cost reduction of their manufacturing process are critical to achieve this objective.[9] The selected demonstrator (**bell housing**) is currently made in nodular cast iron, but the new LPSC process will permit to manufacture bell housings in aluminum alloy. This may drastically reduce the weight and the need of posterior machining which directly influences in the cost.

2.- Experimental

Firstly, requirements to be fulfilled by each of the two demonstrators have been set up to validate the LPSC process. Table 1 collects the list of requirements. In the case of the cylinder head, the different parameters are compared with the values currently obtained with the A319 aluminum alloy (Al-6%Si-3.5%Cu-1%Fe-1%Zn) processed through LPDC. In the case of the bell housing, these components are currently made in nodular cast iron processed through gravity casting. The requirements for this component are based on the current process and material.

Second step has been the design of the mold for each of the demonstrators. The cylinder head is already being manufactured through aluminum LPDC, therefore, current design has been modified according to the needs of the LPSC process. These needs include the application of squeeze pressure in the combustion chamber zone, the most critical area of this structural part of the engine. The extra pressure applied improves the contact between the aluminum and the mold walls, increasing the heat transfer rate and thus the solidification rate. Casting simulation tools such as Magma and ProCAST have been used to support the design process of the molds.

For the bell housing, a completely new mold has been designed. A Finite Element Analysis (FEA) has been done on both the current design and the new design to model how the torque and radial/axial forces affect the component. This analysis has allowed to obtain an aluminum alloy part design with a comparable stress distribution with the current cast iron part.

Mold modifications have been performed including the addition of the extra hydraulic piston to apply the squeeze pressure and the modification of the drag cooling system. To increase the solidification rate of the part critical areas, the cooling system has been modified to work with water instead of air as cooling media.

Later, the prototype casting machine used for the validation of the process has been adapted to hold the new molds and the control system has been modified to integrate the squeezing steps in the process. The introduction of this step transforms the LPDC process into the new LPSC process. The main changes implemented have included the addition of programming lines and control electronics to the current PLC system to manage the application of the squeeze pressure and the water cooling circuit. The machine has also required alterations on the part extraction system and the addition of an extra pump to deliver the water at the required pressure and flow rate through the new water cooling lines. A schematic drawing of the LPSC casting machine used for the validation of the developed process is shown in Figure 1.

After setting up the modified machine, preliminary trials have been performed to evaluate the feasibility of applying the proposed enhanced LPSC process with modified tooling in the production of automotive cylinder heads. The main aspects considered in the technical viability study have included the ability of the sand cores to withstand the squeeze pressure without breaking and avoiding penetration of aluminum. Solidification control with the water cooling system has also been evaluated to avoid freezing of the mold ingates before the injection period was completed.

In the trials, some parameters have been studied and adjusted (Table 2). It has been seen that the application of pressure values higher than 400 mbar lead to severe sand core penetration, while values lower than 300 mbar produced very high shrinkage porosity in the casting mid-section. The pressure must be applied immediately after filling the cavity, one second delay maximum, to avoid the alloy solidifying before the application of the squeeze sequence. This sequence starts with the movement of the squeeze punch which is displaced 2.0mm at a velocity of 0.5mm/s and finishes with the return of the squeeze punch to its initial position once the solidification is completed. Finally, it has been seen that cooling down the combustion chamber zone of the cylinder head with water reduces the drag temperature required without affecting negatively to the mechanical properties.

A first batch of 35 parts has been cast in aluminum A356 alloy (Al-7%Si-0.25%Cu-0.2%Fe-0.4%Mg) using optimized parameters obtained for the cylinder head LPSC process (330 mbar of furnace overpressure, release of the squeeze pressure one second after the mold was full, and water as cooling medium). Another batch of parts has been cast in the same alloy using conventional LPDC process to compare the microstructure and the tensile properties. T6 heat treatment has been applied to all the castings solutionizing the cylinder heads at 530ºC for 5 hours, followed by water quenching at room temperature and artificial ageing at 180ºC for 5 hours.

X-ray inspection has been used to observe the presence of any sand penetration from the core in the part. The microstructure in the "as-cast" and in the heat-treated parts has been studied with an optical microscope and the Secondary Dendrite Arm Spacing (SDAS) has been measured using the linear intercept method on optical micrographs. Five representative micrographs have been obtained for each sample and the average value of the SDAS of the five measurements has been calculated.

For materials with dendritic structures, the SDAS is most commonly characterized as the microstructural feature analogous to grain size in wrought structures. Decreasing SDAS has been found to increase strength and hardness, reduce interdendritic shrinkage porosity,[10] and influence electrical and thermal conductivity.[11] Tensile specimens have been machined from the critical area (combustion chamber) of the treated parts. Figure 2 shows the region of the cylinder head from which the specimens have been extracted. Tests have been performed following ASTM E-8 standard at room temperature (RT) and 150ºC (HT). Low cycle fatigue performance has also been measured following ASTM E-606 standard at 150ºC. Finally, thermal conductivity has been measured at room temperature, 150ºC, and 200ºC.

A similar process has been repeated for the bell housing. The new mold has been mounted in the same casting machine and modifications in the casting cell have been implemented. Two casting trials have been performed to set the optimum casting parameters, mainly those related to the cycle time. At the end, a total cycle time of 330 seconds has been set with the molten aluminum introduced at 745ºC. With these parameters, a batch of 16 parts has been produced to perform the required characterization. The most critical areas defined by the FEA has been cut from the parts and tensile specimens have been machined and tested. Tensile tests at room temperature have been carried out to measure the ultimate tensile strength.

Corrosion tests have also been performed following the standard EN-ISO 9223 which defines the corrosivity of the atmosphere according to corrosion rate of various metallic materials. It stands that for a C4 atmosphere (industrial areas and coastal areas with moderate salinity) the aluminum should not lose more than 5 g/m^2 in the first year of exposition (75 g/m^2 after 15 years of service assuming the corrosion rate is constant with time). To simulate a C4 atmosphere, two different tests were carried out: 480 h of water condensation (standard ISO 6770) and 720 h of neutral salt spray (ISO 9227).

3.- Results and discussion

With the optimized process parameters, a batch of 35 cylinder heads has been cast and heat treated. The X-ray inspection has revealed that 100% of the parts were free of sand penetration.

The SDAS measurements at the combustion chamber zone of the cylinder head gave values between 25 and 27 µm, lower than those from the castings processed with LPDC process. The measures taken in the "as-cast" samples also show lower SDAS average values in the parts processed through LPSC (Table 3). This is attributed to the higher solidification rate due to the squeeze pressure applied in that zone of the part. The reduction of dendrite size, which can be observed in the optical micrographs in the "as-cast" samples (Figure 3), is in agreement with the relationship between SDAS and cooling rate (CR) typically reported by the following equation:[12]

$$SDAS = \mu_1 (CR)^{-0.34 \pm 0.02} \quad (1)$$

where μ_1 is a material-specific constant.

Figure 4 shows the strength results obtained for these castings in comparison with the results obtained for the same alloy processed through the conventional LPDC process. Castings processed through the innovative LPSC process show higher values of strength at both room temperature and 150ºC: yield strength increases from 190 to 240 MPa at room temperature and from 180 to 235 MPa at 150ºC, while ultimate tensile strength increases from 255 to 300MPa at room temperature and from 220 to 250 MPa at 150ºC. This can be explained by the refined microstructure derived from the faster cooling process. Refinement of the primary structure increases the grain boundary area in the material. Grain boundaries in turn, are effective barriers to dislocation movement, since there is a discontinuity of slip planes and a crystallographic misorientation between adjacent grains.[13] As dislocation movement is impeded across boundaries, plastic deformation is restricted strengthening the material. The strengthening associated with grain size decreasing is generally represented by the Hall-Petch equation:[13]

$$YS = \mu_0 + \mu_y d^{-1/2} \quad (2)$$

where YS is the yield strength, d is the average grain diameter and μ_0 and μ_y are material-specific constants.

Concerning the ductility, higher elongation values are obtained both at room temperature and 150ºC for the castings processed through LPSC process (Figure 5). This is also thought to be mainly related to the refined microstructure and the lower SDAS, as observed by Shi et al.[14] who set the following relationship between the elongation (ε) and the SDAS for a A356 alloy:

$$\varepsilon = 1.13 + 211.1(SDAS)^{-0.96} \quad (3)$$

For an average SDAS of 26.6 μm obtained in these castings, an elongation value of 10.2% would be obtained according to the equation 3, which is in agreement with the experimental finding.

In close relation to the higher elongation, low cycle fatigue performance at 150ºC of the LPSC parts is better as it is shown in Figure 6. The higher solidification rate leads to a lower SDAS and a reduced porosity of these castings. The measurements made in the castings confirmed this porosity reduction, which was reduced from 0.5vol.% in the parts processed through the conventional LPDC process to 0.25vol.% in the parts processed to the innovative LPSC process. These aspects have been signaled to have a direct influence on the increase in the low cycle fatigue performance, as it is explained in the different works. [15-16]

Thermal conductivity is also higher for the castings produced through the LPSC process for the whole range of temperatures (Figure 7). The lower porosity of the castings due to the squeezing action is responsible of the increase in the thermal conductivity, as it is also expressed in the study carried out by Ramirez-Manzano et al.[17] Moreover, the reduction in the dendrite size has also a positive effect in the conductivity as found by Vázquez-López eta al.[18]

In the case of the bell housing, ultimate tensile strength values of 265 MPa have been obtained, higher than the 250 MPa set in the requirements.

Machinability was also analyzed, concluding that the aluminum parts could be machined at a higher speed and with a reduced wear of the machining tools. Overall time for machining the part could be reduced from 15 minutes to 8.5 minutes and the total weight of the final part was decreased from 24 to 9 kg., decreasing the weight more than 50%.

Table 4 shows the specific weight loss of the samples tested for corrosion C4 environment simulation of 15 years' service. Values obtained on both trials are lower than the maximum value of 75 gm^{-2} indicated in the standard. Accordingly, the viability of the bell housing produced through the LPSC process to be used in corrosive environments has been demonstrated.

4.- Conclusions

A new LPSC process has been developed based on the conventional LPDC process along with the application of an extra pressure during the solidification process to increase the solidification rate.

The process has been validated through the production of two demonstrators. For the cylinder head, higher mechanical properties and fatigue life have been achieved in the combustion chamber, the critical area of this component. The increasing in mechanical properties has been obtained improving mold cooling conditions and squeezing the liquid alloy which enhanced the contact between the aluminum and the mold. Therefore, higher solidification rates have been reached and in consequence lower porosity and better mechanical properties have been achieved.

The lower porosity is also responsible for the increased thermal conductivity, which will certainly be reflected in a better component performance during the engine operation.

The LPSC has been also validated producing a batch of bell housings. It has been demonstrated that changing the production process and the material from gravity cast nodular cast iron to aluminum processed through the new LPSC process leads to a very important weight reduction of the final part and an important reduction of the machining costs, as the machining time of each part is reduced around 40%. The required strength properties are achieved and the 15 years of service life in C4 environment are reached.

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TABLES

Table 1. Requirements for the validation of the technology for each demonstrator comparing with the current technology and materials.

Requirements	Cylinder head	Bell housing
Strength	20% increase at the combustion chamber zone	>250MPa
Fatigue resistance	Increased fatigue life	Not considered
Weight	At least same weight	More than 50% reduction
Productivity	At least same productivity (10/11 castings/hour)	Higher productivity
Castability	At least same castability	At least same castability
Machining	Not considered	Reduction of the machining time
Corrosion resistance	Not considered	More than 15 years in service protection
Cost	Increase not higher than 10%	More than 20% reduction

Table 2. Process parameters studied in the cylinder head castings.

Parameter	Studied range
Applied pressure	270 – 500mbar
Squeeze application time	1 – 5 sec.after mold full
Cooling medium	Air and water

Table 3. SDAS of cylinder heads castings processed through LPDC and LPSC processes. Average values and standard deviation are given

Condition	LPDC	LPSC
As-Cast	73.6 ±5.3	40.8 ±4.7
T6	48.6±3.2	26.6 ±1.8

Table 4. Corrosion test results

Process	Surface area [cm^2]	Weight loss [g]	Specific weight loss [gm^{-2}]
480h water condensation	137.61	0.0613	4.455
720h salt spray	136.82	0.4172	30.493

FIGURES

Fig. 1. Low Pressure Squeeze Casting machine drawing

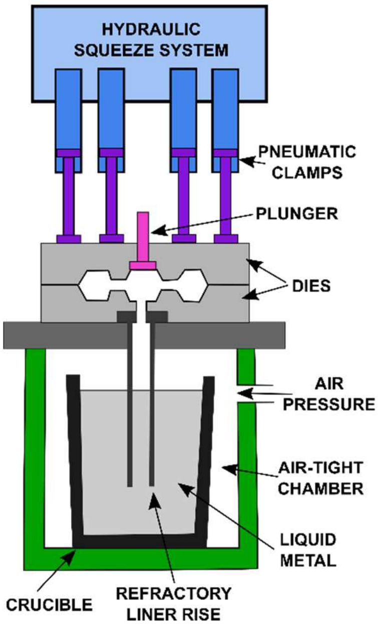

Fig. 2. Cylinder head. Red points and bar show the location of the testing specimens

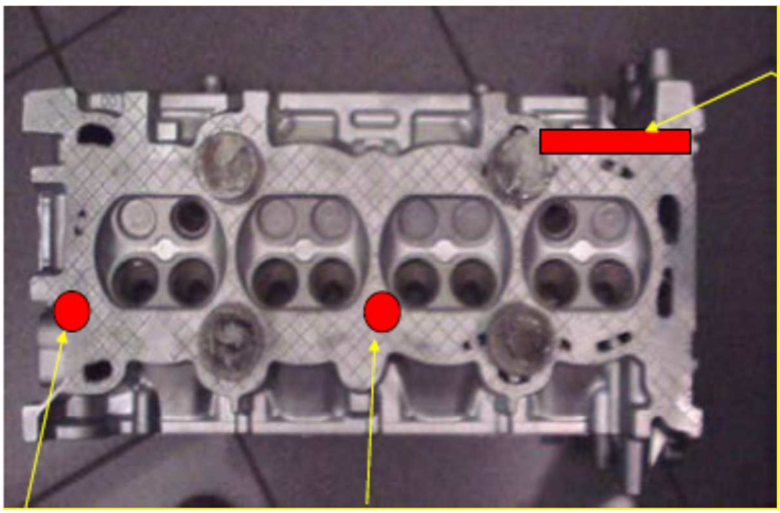

Fig. 3. Optical micrographs at 100 magnifications of A356 "as-cast" samples of parts processed through (a) LPDC and (b) LPSC processes

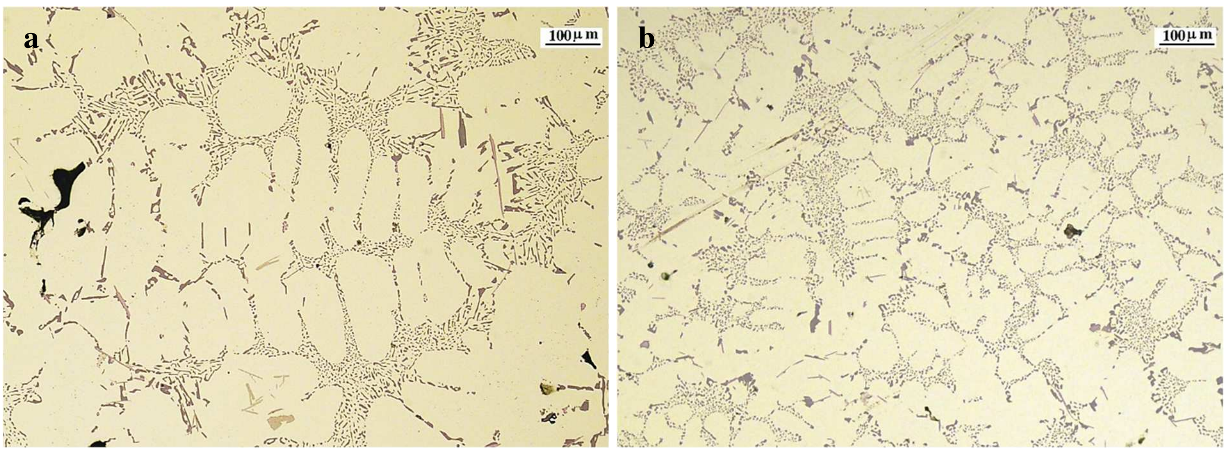

Fig. 4. Yield Strength (YS) and Ultimate Tensile Strength (UTS) at room temperature (RT) and 150ºC (HT) for T6 treated A356 casting components processed through LPDC and LPSC processes

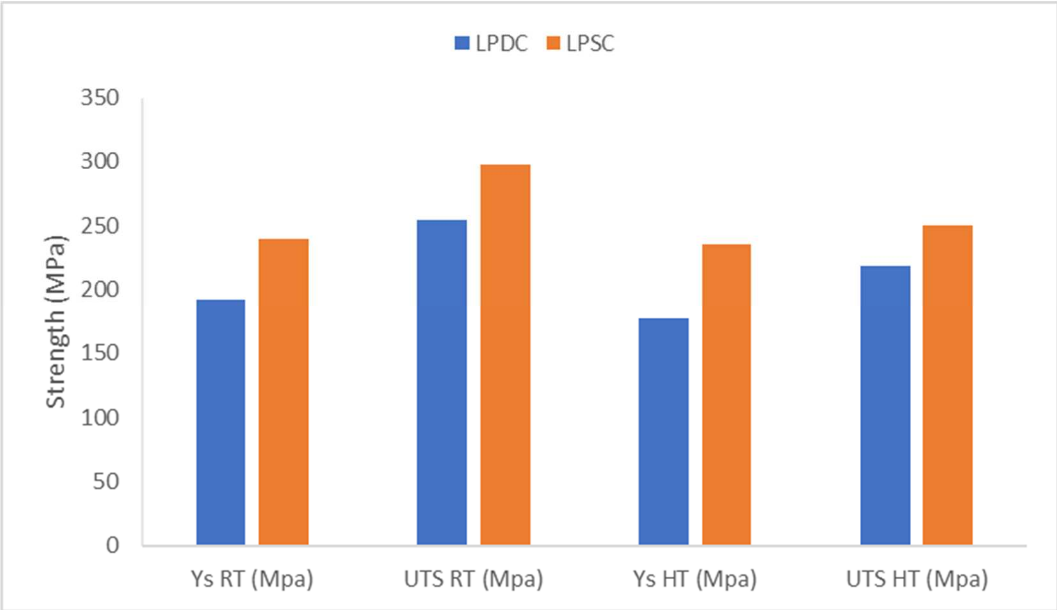

Fig. 5. Elongation as a function of temperature for T6 treated A356 casting components processed through LPDC and LPSC processes

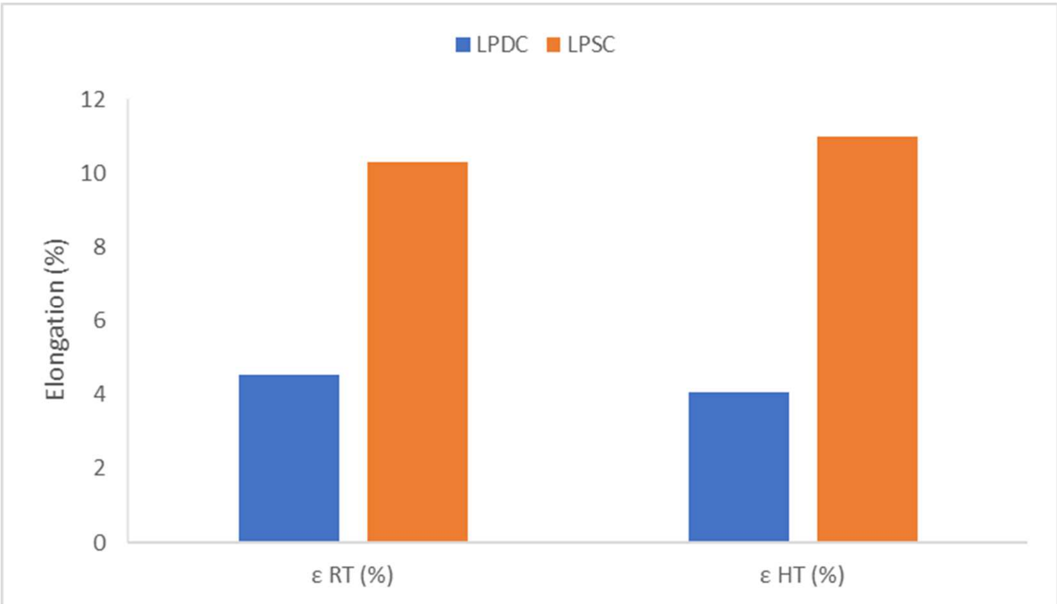

Fig. 6. Low cycle fatigue for casting components processed through LPDC and LPSC processes

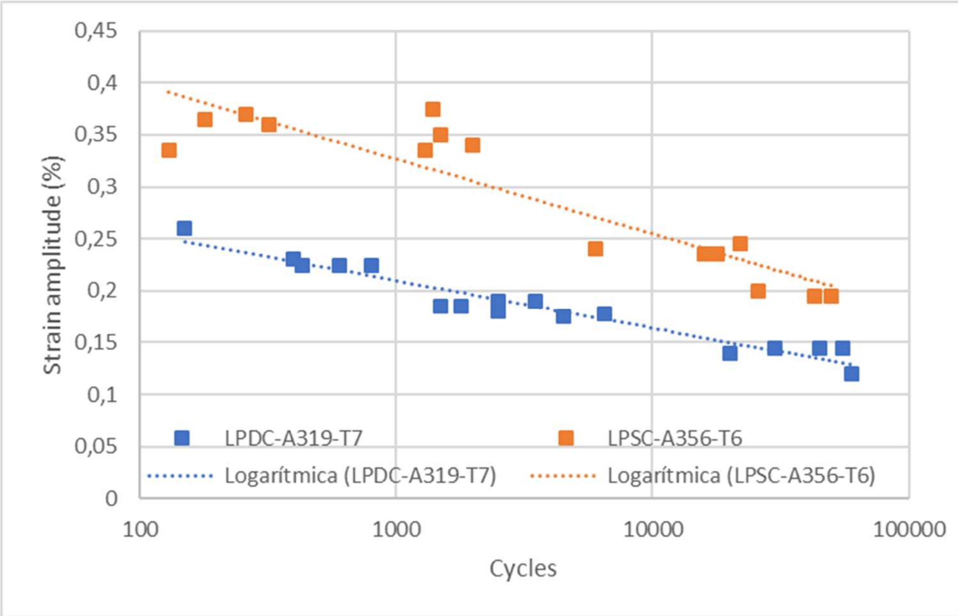

Fig. 7. Thermal conductivity as a function of temperature for casting components processed through LPDC and LPSC processes

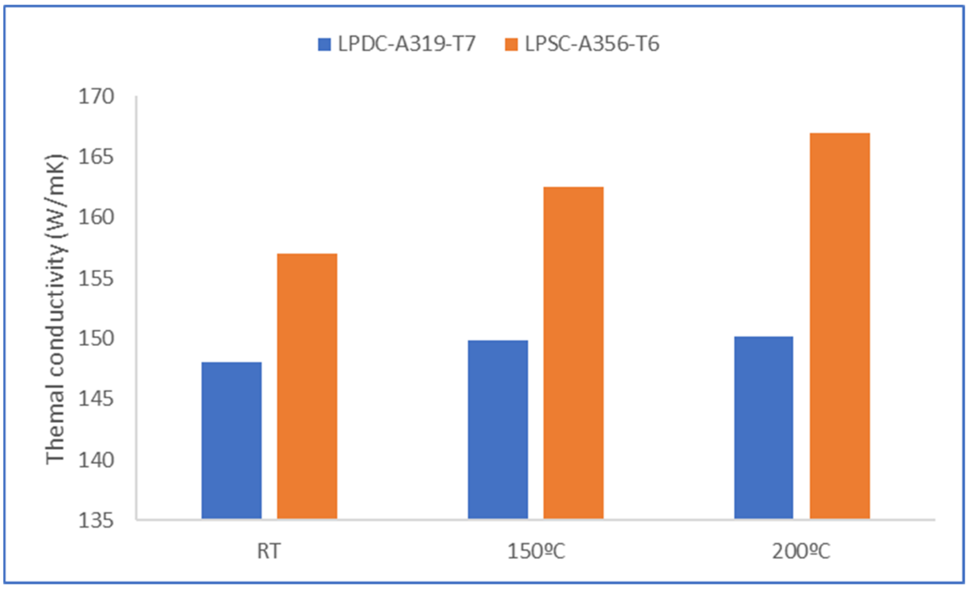

TABLE OF CONTENTS

The use of aluminum cast components is continuously increasing in relevant industries such as the automotive and energy. Complex parts are usually manufactured though Low Pressure Die Casting processes, but the increase in the efficiency demands of these industries is forcing to develop advanced processes. The Low Pressure Squeeze Casting presented in this paper is one of them. It combines the possibility of producing complex designs with improved mechanical properties thanks to the application of a specific pressure in the mold during the solidification process.