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Evaluation of the Influence of Process Parameters on the Mechanical Properties of Castings during High Pressure Die Casting

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The article is devoted to the influence of mold filling parameters by the HPDC - High Pressure Die Casting method on the mechanical and structural properties of castings intended for technology and mechanization means in forestry. Three groups of AlSi10MnMg alloy samples were formed for the experiment. Three different settings of mold cavity filling parameters were chosen. Two castings were made from each setting. Two samples were taken from two places on the casts. Thus, 12 pieces of samples were used for the experiment. An analysis of their mechanical properties was performed using a static tensile test. tensile strength, yield strength and ductility were evaluated. The microstructure was evaluated by light optical microscopy. The influence of process parameters on the quality of the casting was monitored from the point of view of the occurrence of errors, defects and the method and size of the exclusion of structural phases. The experimental results showed that the best results were obtained when the process parameters of the first group of samples were set. Their values are the closest to the customer's requirements.

Keywords: forest technology, HPDC - High Pressure Die Casting, mechanical properties, microstructure, AlSi10MnMg

1 Introduction

In forest technology, the use of chainsaws is an essential part of harvesting, processing and handling wood. The components of which they are composed are made of different materials and with different technologies [1, 2]. Some of them are castings, mainly of aluminium alloy. Aluminium alloys are quite strong but at the same time have a lower weight than iron-based alloys. Al-Si based alloys with their properties such as low density, high strength, good corrosion resistance, weldability, meet the requirements placed on various components of forest technology. Due to the constructional complexity, size and observance of minimum wall thicknesses, especially in their design, the most suitable manufacturing technology for their production seems to be High Pressure Die Casting HPDC - High Pressure Die Casting. High-pressure casting of aluminium components is currently a fully automated process for high-volume production, using the most modern methods of setting, controlling and monitoring individual casting production parameters. The high demands on the internal homogeneity of castings as well as on the mechanical properties are forcing manufacturers to continuously improve their processes by optimizing metal preparation, high-pressure mould filling, and controlling and maintaining the mould's thermal regime. Commercial AlSi10MnMg alloy is widely used for making castings by HPDC for various fields. The correct setting of the HPDC technological parameters will ensure a quality casting that will meet the requirements applicable to this part of the device. The basic prerequisite for achieving optimum mechanical properties for castings cast by HPDC in the post-casting state is the setting of the casting process parameters to obtain a homogeneous structure without or with a minimum porosity value and to achieve optimum values of mechanical properties [3].

2 Material and methods

In addition to the technical and technological properties of chainsaws, the weight of this equipment is still important. Although [1] states that the mass factor of saws is not relevant due to the rapid technical development of chainsaws, it is still important to think about the personnel operation of these devices. Fig. 1a shows the engine part of the saw. Fig. 1b is a detail of the engine block, which is cast from an aluminium alloy.

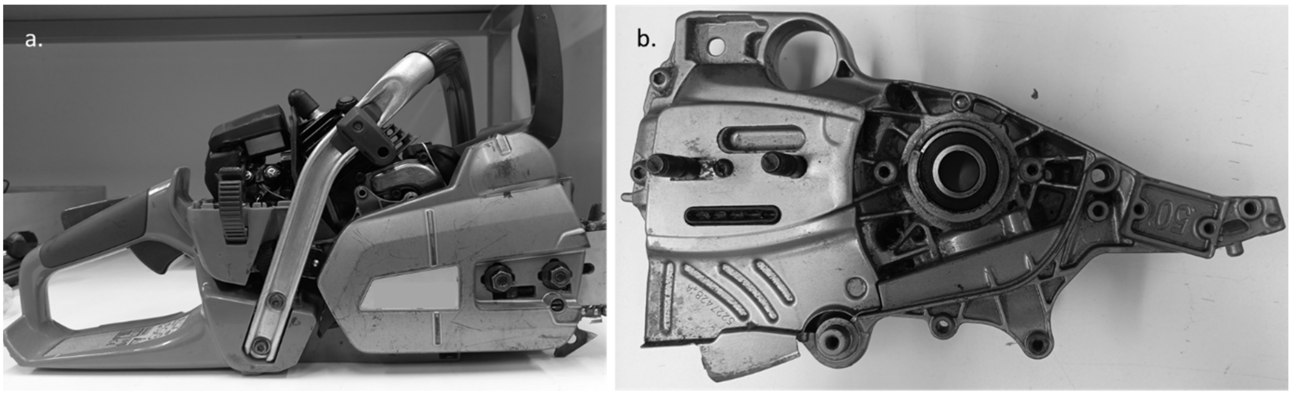

Fig. 1 *Engine part of a chainsaw (a.); detail of engine block (b.)*

Die casting is characterized by the replacement of gravitational metallostatic pressure by the force action of a piston on the melt in the filling chamber of a die casting machine. The piston, at a high speed (on the order of units of m^{-1}), transports the melt from the filling chamber through the sprue system into the mould cavity through the notch. In it, the melt flow speed is several tens of meters per second. It follows from the above that the total time of filling the mold cavity is very short, units to tens of milliseconds. This method of filling the mold cavity enables the production of thin-walled, shape-demanding castings with high dimensional accuracy and with exact copying of the surface relief of the mold cavity [4].

Mold filling in the aluminium die casting process of high-pressure die casting is the most important process parameter. During the filling of the mold cavity, we monitor the filling speed in a certain piston path and the piston pressure [5]. When the filling piston is in the rightmost position, the chamber is filled with liquid metal. In the first phase, the piston moves at a very low speed of about 0.1 $m.s^{-1}$ until it safely covers the chamber filling opening. After the stroke of the piston has passed in the first phase, there is also a slight increase in the liquid metal level. The speed of the first phase is constant, it cannot be changed [6].

The second phase - pre-filling at the beginning follows the first phase. We use the clearance between the press piston and the chamber bore to escape some of the gases above the surface. Therefore, the speed of the second phase is also small v=0.1 to 0.4 $m.s^{-1}$. At high filling speeds, air entrainment can occur in the chamber resulting in air porosity (bubbles), underfilling, cold welds or blisters. At low filling speeds, under-polishing, cold welds, surface defects of the casting due to supercooling of the liquid metal may occur. At low filling speed, under-polishing, cold welds, surface defects of the casting due to supercooling of the liquid metal may occur. The second phase lasts until the liquid metal level in the filling chamber rises to the level of the inlet notch [6]. In the third filling phase, the speed must be such that the mold cavity is filled at the optimal time or the alloy speed in the notch is equal to the optimal speed [6,7]. The forces acting on the press piston in the first and second phases must be large enough to overcome the resistance of the pressing mechanism at the selected speed. The size of the pressing force at the end of the third phase, the filling phase, depends on the cross-sectional area of the filling chamber and the pressure on the alloy. Incorrect selection of the filling phase speed can lead to underfilling, cold joints, air and gas porosity [3,8]. Defects occur when the speed is insufficient. On the contrary, at excessive speed in the filling phase, there is an increased risk of air sealing in some parts of the mold, the formation of oxide inclusions, mould deformations, as well as the formation of burrs in the parting plane. This phase ends with filling the mold cavity with metal and stopping the piston [3,6].

The course of pressing force and speed in individual phases is graphically shown in Figure 1. At time t_1 and t_2 (first and second phase) a slight increase in speed and pressure is observed. At time t_3 (the third phase of pressing), we observe a maximum increase in speed and a slight increase in pressure, after the end of this phase, the mold cavity is filled with metal. At time t_4 (overpressure) there is an enormous increase in pressure. This means that the piston is pushing on the tablet.

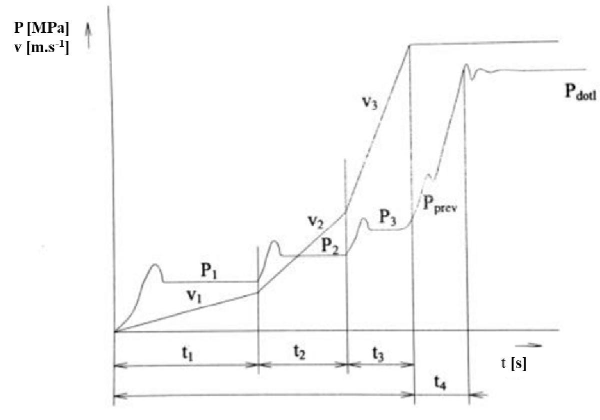

Fig. 2 *Force and speed in individual phases [6]*

To verify the influence of the process parameters of filling the mold cavity on the values of the mechanical properties and structures of the castings, test castings were performed.

The liquid metal of EN AC-AlSi10MnMg alloy was poured into the holding furnace using a transfer pan. The temperature of the liquid metal was maintained at 750 °C and during the experiment the metal was refined using an inert gas - argon. The chemical composition of the melt is shown in Table 1.

Tab. 1 *Chemical composition of AlSi10MnMg melt for casting samples*

Chemical element	Si	Fe	Mn	Mg	Ni	Zn	Sr	Ti	Al
wt. %	10.83	0.106	0.515	0.31	0.003	0.013	0.017	0.065	rest

Three different settings of mold cavity filling parameters were chosen for the experiment. Two castings were made from each setting. Samples were taken from two places on the castings to check the mechanical properties and to evaluate the structure.

12 samples were prepared for the experiment (Table 2):

- first group - designation E - castings cast at the current, serial production parameters, namely at the speed of piston movement at the end of the prefilling phase path v=0.25 m.s^{-1} and setting the overpressure to the value p=21 MPa, number of samples - 2 pcs from each casting, total of 4 pcs of samples.
- second group - designation P - cast by modifying the second, so-called prefilling phase. The value of the piston movement speed at the end of the path of this phase v=2.5 m.s^{-1}. It is 10 times more compared to the first group of samples - the number of samples - 2 pcs from each casting, a total of 4 pcs of samples.
- the third group - designation R - cast using lower speeds compared to serial production. Overpressure setting p=15 MPa. It represented a decrease in pressure compared to the samples cast in the first and second groups by 6 MPa, the number of samples – 2 pcs from each casting, a total of 4 pcs of samples.

Tab. 2 *Setting the HPDC technological parameters for the experiment*

Groups of samples	Speed of piston movement v [m.s^{-1}]	Piston overpressure p [MPa]	Number of samples
First group E	0.25	21	4
Second group P	2.5	21	4
Third group R	0.18	15	4

2.1 Static tensile test

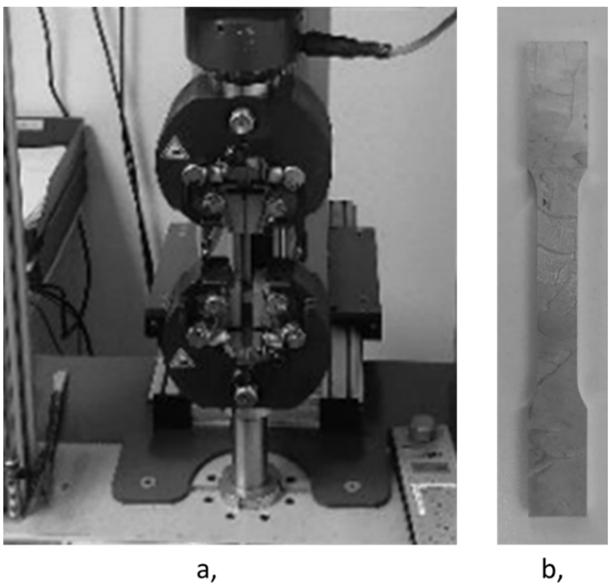

Fig. 3 *Static tensile test; a, clamping detail of test specimen; b, test specimen*

To determine the mechanical properties, a static tensile test was used, performed on an Inspect desk tensile testing machine, with a maximum loading force of 50 kN (Fig. 3a) according to EN ISO 6982-1:2019 [9]. The thickness of the test specimens was equal to h=6.0 mm (Fig. 3b).

2.2 Metallographic analysis

After the static tensile test, parts were taken from the ruptured specimens, which were prepared in dentacrylic resin and ground using a 600 grit grinding wheel to observe the microstructure. For coarse polishing, Alergo largo 9 μm suspension, MD largo disc was used, followed by fine polishing with DAC 3 suspension, MD DAC disc. Finally, the samples were polished on an MD CHEM disc using OP S suspension. The structure was observed with a Leica DMI 5000M optical microscope.

3 Results and discussion

To compare the measured values of tensile strength Rm, yield strength Rp0.2 and ductility of the specimens A in the static tensile test, Table 3 was compiled. Two samples were taken from each casting. From these, the average for each single casting was calculated. Although at least 3 pieces of data are required for statistical evaluation, in our case the average was calculated as the value that is drawn per cast piece.

Tab. 3 *Determined and calculated values of Rm, Rp0.2 and A after static tensile test*

Groups of samples	Marking of samples	Tensile strength Rm [MPa]			Yield strength Rp0.2 [MPa]			Ductility A [%]		
		x	$\bar{x}$	$\bar{\bar{x}}$	x	$\bar{x}$	$\bar{\bar{x}}$	x	$\bar{x}$	$\bar{\bar{x}}$
First group E	1A/E	262	261.5	261.75	188	180.5	178.5	7.1	6.4	5.5
	1B/E	261			173			5.7		
	2A/E	258	262		174	176.5		3.2	4.7	
	2B/E	266			179			6.1		
Second group P	1A/P	262	261.5	262	176	174	173	7.5	7.1	8.25
	1B/P	261			172			6.7		
	2A/P	263	262.5		174	172		8.5	9.4	
	2B/P	262			170			10.3		
Third group R	1A/R	265	268.5	266.75	174	176	180.5	4.2	4.6	5.45
	1B/R	272			178			4.9		
	2A/R	265	265		190	185		5.9	6.3	
	2B/R	265			180			6.6		

Tab. 4 *Values of mechanical properties required by the customer*

Tensile strength Rm_{min} [MPa]	Yield strength Rp0.2 [MPa]	Ductility A [%]
215	150	7

The values of mechanical properties required by the customer are given in Table 4.

From the values in Table 3 and Table 4, a graph was constructed (Fig. 4). It shows that changing the mold cavity filling parameters resulted in only a slight increase in the values of Rm and Rp0.2. As can be seen from the graph, the ductility of A for the group of samples E and R decreased.

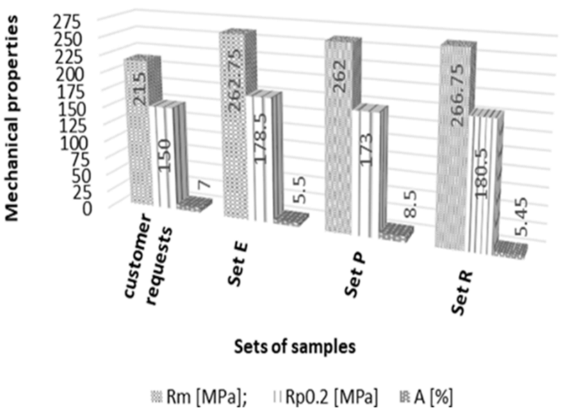

Fig. 4 *Graph of mechanical property values – comparison*

To evaluate the microstructure of the material, microscopic analysis by optical light microscopy was performed. Figures 5 to 7 show a typical structure observed on the samples near the fracture line with a description of the main phases. It can be seen from the figures that the main phases in the microstructure are α-phase and eutectic silicon. There are also a small number of plate-shaped formations in the structure. Due to the chemical composition of the melt used for casting the samples, it is probably manganese-rich phases. By varying the process parameters, no changes were observed in the method and size of the precipitation of structural phases. The main phases were α-phase and eutectic silicon, which are described in Figure 5b. Relatively large α-phase dendrites with the presence of secondary arms were present on all observed samples. This can be considered as a non-standard manifestation in the solidification process of thin-walled castings cast by the HPDC method. Eutectic silica was sufficiently modified by the addition of the element Sr on all samples. This is, from the point of view of achieving maximum plastic properties, the desired state.

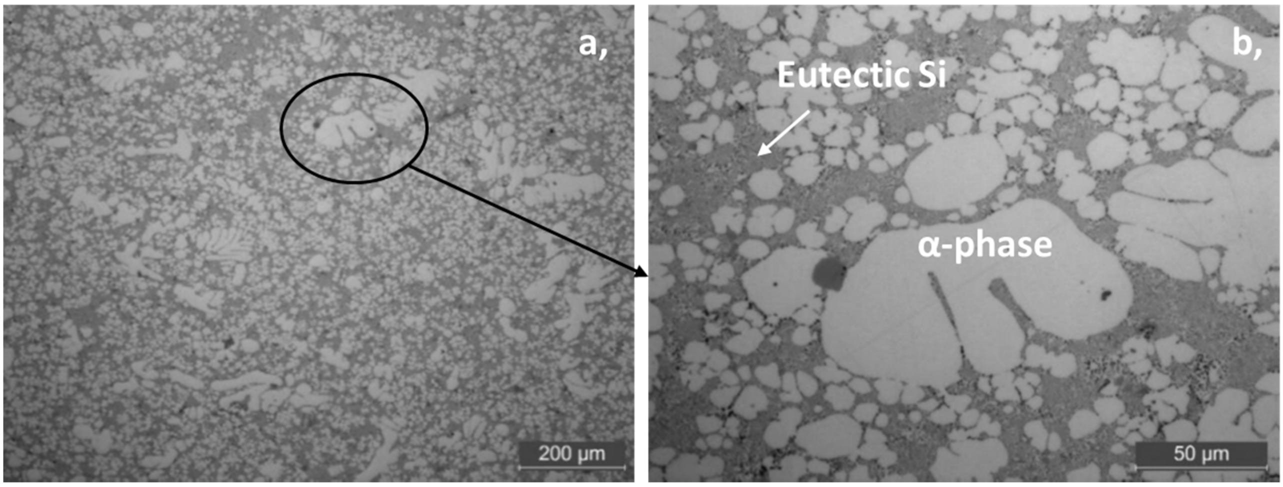

Fig. 5 *Microstructure of the sample material - first group* E

A greater number of defects were observed on the P and R group samples. They were predominantly porosity and oxides. Their presence was probably caused by a change in the setting of the experimental parameters of the mold filling process (Fig. 6 and Fig. 7).

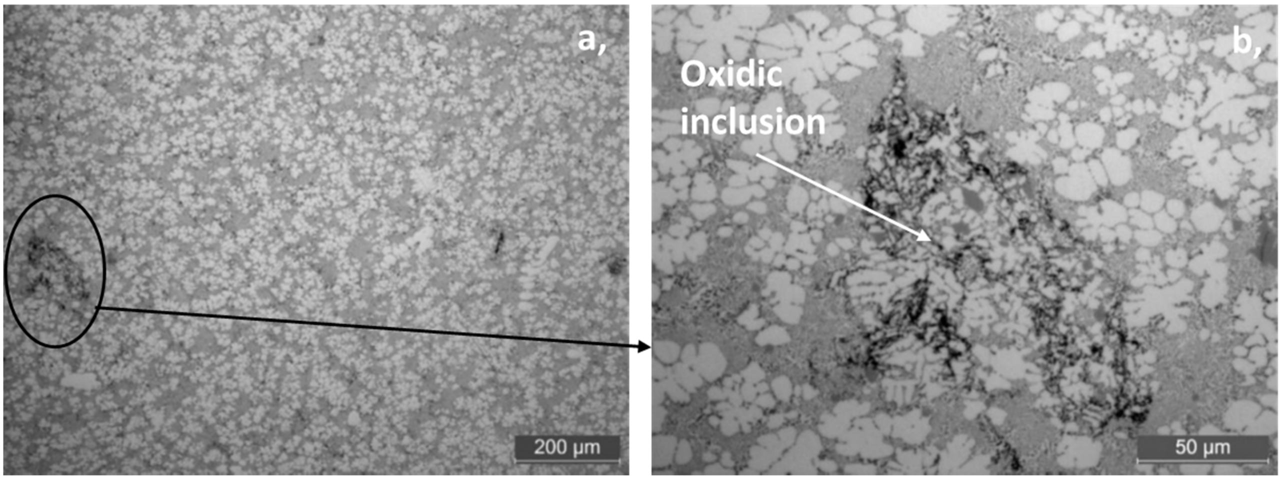

Fig. 6 *Microstructure of the sample material – second group P*

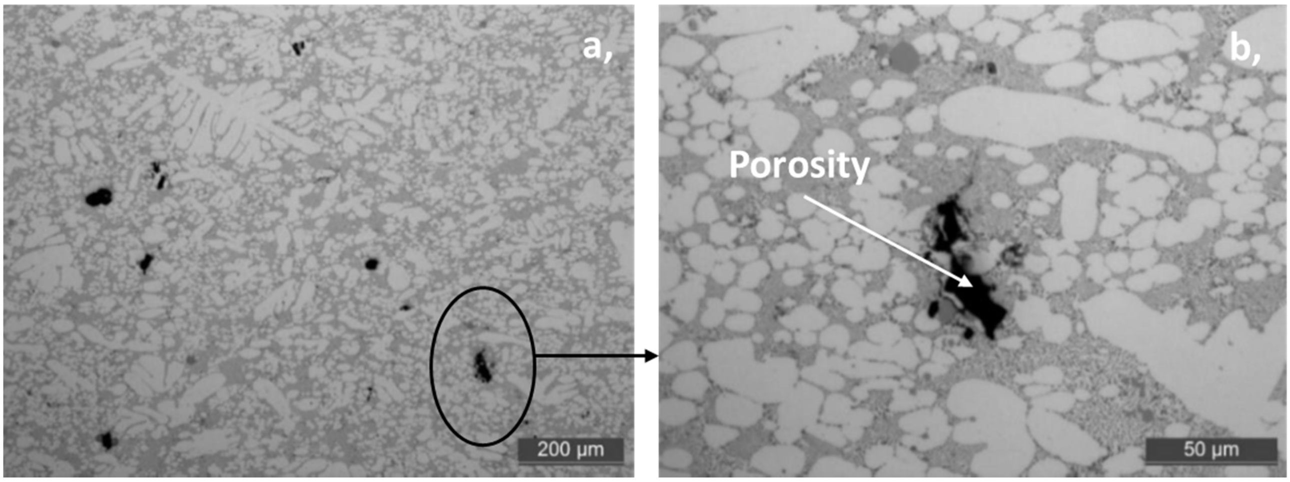

Fig. 7 *Microstructure of the sample material – third group* R

Aluminium alloys are often contaminated with non-metallic inclusions. A large number of these phases accelerates the porosity tendency of castings, significantly reduces corrosion resistance and primarily affects mechanical properties [3,11].

The authors [10,12,13] studied the mechanisms of modification of the properties detected by means of tensile tests, hardness measurements and microstructural observations made on HPDC castings. Low pressure and low temperature increase the rate of porosity, promote the formation of coarse Fe-rich intermetallic compounds and change the morphology of α-Al phases. These in turn deteriorate mechanical tensile properties. However, variation of alloying elements contents modifies the optimum properties achieved when part is made at constant casting processing parameters. Finally, the interactions between the studied parameters of HPDC and the chemical alloying elements show also a significant influence on the tensile properties.

Based on the experimental results, we can conclude that the values of tensile strength and yield strength were not changed by adjusting the casting parameters - group P and group R specimens compared to group E specimens cast at serial casting parameters using the HPDC method. The maximum average value of both tensile strength and yield strength was obtained on the specimens of group P. The average value of tensile strength on specimen P was 268.5 MPa, which is 6 MPa higher than the measured value on the specimens cast with the series parameters. The average yield stress value on specimen P was 185 MPa. This is 13 MPa more than the measured value on the specimen cast at series production parameters. All values of strength properties (Rm, Rp0.2) were in accordance with the customer's requirement.

The required ductility values were achieved only for castings cast at series production parameters - group E. The maximum average yield value was 9.4%, while the maximum ductility values on samples R were 6.4% and P 6.3%.

Based on the above results, it is evident that no changes in the mode and magnitude of deposition of the structural phases were observed by varying the process parameters. The main phases were α-phase and eutectic silicon. All observed samples showed relatively large α-phase dendrites with the presence of secondary arms, which is a non-standard manifestation in the solidification process of thin-walled castings cast by the HPDC method. Eutectic silica was sufficiently modified by the addition of Sr for all samples. This is the desired state from the point of view of achieving maximum plastic properties. A greater number of defects were observed on the R and P samples. They were mainly porosity and oxides. Their presence was probably caused by the modification of the observed process parameters of the mold filling process.

The increase of the mold filling speed in the prefilling phase as well as the changes in the overpressure setting in the last phase did not have the expected effect on the strength properties values, while the ductility A values, probably due to the occurrence of internal defects, decreased compared to the serial setting of the monitored HPDC parameters.

4 Conclusion

Considering the above experimental outputs, from the point of view of long-term observation, we can consider the setting of the process parameters of mold cavity filling at HPDC, which affect the mechanical properties Rm, Rp0.2 and A structure of the castings to meet the customer's requirements, to be truly optimum.

An important point for the serial process remains the increase of the ductility A values. Ductility limits may be inappropriate from the customer's point of view in the long term. Therefore, it is necessary to carry out complex optimization tests, which will also include testing of the modification and chemical composition of the melt, the thermal regime of the mold, or testing of the above parameters in combination with the parameters of the mold filling process.

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