J Braz. Soc. Mech. Sci. Eng. (2017) 39:3079–3088
DOI 10.1007/s40430-016-0672-x

TECHNICAL PAPER

Experimental and numerical simulation study of porosity on high-pressure aluminum die casting process

D. Concer[1,2] · P. V. P. Marcondes[2]

Received: 10 November 2015 / Accepted: 4 November 2016 / Published online: 14 November 2016

Abstract The resulting porosity is responsible to 70% of failures on the high-pressure aluminum die casting process. The determination of the origin and setting the pore elimination is a complex mechanism. There are several factors that induce their occurrence. Thus, it is common to employ process and engineering alternatives to try to solve the issue. Faced with such complexity we tried to understand how to apply the finite element methods to minimize the occurrence of pores in high-pressure die casting products. The objective of this study was to develop a methodology to generate an equation that represents the porosity behavior aiming to determine the best engineering and process settings to reduce the pore volume in aluminum injected products. The aim of this study was to develop a methodology to generate an equation that represents the porosity behavior. To do that, the results obtained with the variation of some boundary conditions which were applied to computer simulations in commercial dedicated software were analyzed. It was observed that a flow and solidification analysis of the product in the mold can determine the probability of occurrence of pores in the product already during injection process.

Technical Editor: Márcio Bacci da Silva.

✉ P. V. P. Marcondes
marcondes@ufpr.br

D. Concer
dionei@fbmoldes.com.br

[1] Fabrica Brasileira de Moldes LTDAFBM, Joinville, Brazil

[2] Departamento de Engenharia Mecânica, PGMEC
Universidade Federal do Paraná, Curitiba, PR, Brazil

Keywords High-pressure aluminum die casting · HPDC · Aluminum · Porosity · Numerical simulation

Abbreviations

ASTM	American society for testing material
CAD	Computer aided design
CAE	Computer aided engineering
HPDC	High-pressure die casting
FEM	Finite element method
nadca	North American die casting association

1 Introduction

Cars are being increasingly used requiring more durability; however, the useful life is getting faster to the end. The car is a complex product because the mixture of several components, such as, plastic, steel and aluminum that should work in harmony. Unfortunately, there is currently a shortage of natural resources and an increased demand for the recycling of components. The End of Life Vehicle Directive (ELV), launched by the European Union, has determined that automobile recycling rate should reach 85% by 2015 [17].

The interest in aluminum metallurgy and the concern with the porosity of injected aluminum under-pressure products appeared in the decade of 1990. This happened when camshaft bearings were first produced by General Motors and DaimlerChrysler through injection under-pressure process. The manufacture of these products exceeds 100 million units per year for a single motor [19]. Today, the high-pressure aluminum die casting process (HPDC) is responsible for 70% of aluminum products in the market and the automotive industry is the largest consumer. Although the innumerous process advantages of the products obtained by the injection process are limited due to porosity. Such limitations can be characterized by aesthetic defects and reduced structural strength. The solutions of the problems arising from the pores are complex because the injection process parameters are usually set through practical solutions already consolidated—process sampling or trial-and-error procedures. The influence of porosity on the fatigue life in aluminum alloys range from 7.19 to 17%. These numbers were reported for two hypereutectic alloys—AE425 and PM390—and three hipoeutetics alloys—A356-T6, LP PM319-F and C354-T6. It was also found that for 90% of all casted samples that failed as a result of microstructural defects the porosity was primarily responsible for the origin of cracks. Therefore, the porosity is primarily responsible for the reduction in fatigue life and 90% of all products tend to fracture as a result of microstructural defects. Ammar et al. [2] reported that the fatigue resistance decreases as the pore size increases and vice versa.

2 Literature review

It has been found that aluminum alloys produced by high-pressure die casting process (HPDC) usually shows microstructure defects resulting of the casting process, such as porosity, metal oxides and inclusions. X-ray aided analysis is being increasingly used due the ability to provide fast and precise information about porosity [21].

The HPDC process is widely used in industry, especially for product with complex geometries and minimized wall thicknesses—approximately 3 mm. However, the casting process can cause some defects in the injected products and, among all, the porosity is worst. According to NADCA [14] the porosity is the most common problem present in the HPDC process. Porosity is known in the industry as voids formation in the interior of cast products and can be generated by air entrapment in the aluminum matrix during filling, the product mass concentration during solidification or by error in the injection parameters during the process, such as, injection pressure, low volume occupation rate of injection bushing, excess mold release agents and lubricants [16].

This failure is mainly generated by air trapping, derived as a consequence of the turbulence. The turbulent flow behavior is, in turn, generated by high-velocity injection in the die associated with the need of changes direction in the channel to fill the desired product [8]. The demand by cast aluminum products has been increasing, in recent years, especially by the automotive industry which aims constant weight reduction in vehicles to reduce their polluting emissions—mainly because of the aluminum low density of 2.7 g/cm^3. According Klobcar et al. (2007), the HPDC

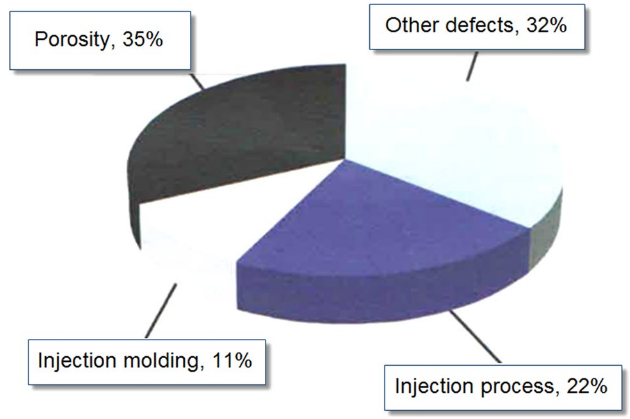

Fig. 1 Distribution of product failures in injected aluminum HPDC process (NADCA [5])

process characteristics are the high and different temperatures, wherein the temperature of the aluminum at the time of injection is about 720 °C.

When aluminum is injected into the mold, the velocities in the feed channel are in the range of 30–40 m/s. Already the injection pressures are in the range 500–1000 bar, depending on the need of thickness and finishing characteristics of the product. It is known that 35% is the default percentage of porosity in a part obtained by HPDC process, Fig. 1. This defect results in low mechanical properties, including load limitations and low ductility, low fracture resistance, irregular beginning of cracks, potentially accompanied by a lack of pressure resistance, therefore, the porosity is considered the main cause for rejection of components obtained by HPDC process. There are two main factors that contribute to the porosity formation in the solidification of Al–Si alloys. The first is the shrinkage resulting from contraction during solidification, as well as, inadequate mobility of the liquid metal, i.e., poor feeding. While the second is the entrapment of gas, mainly hydrogen, that results from the decrease of the gas solubility in the solid metal in comparison with the liquid [2, 11].

Understanding and predicting the porosity in aluminum alloys is difficult because there is a lack of accurate information about the process, mainly related to the diversity of possible injection parameters. Computer simulations do not always represent, satisfactorily, the behavior of the injection process and the complexity of the process and the presence of die temperature gradients can be the cause [13]. Johnson [9] used computer simulation to optimize the logistics inside a bus assembly line. The purpose was to study the behavior and maximize the efficiency of a logistic system, for an assembly line, to find a minimum number of vehicles to specific production rates. The simulations using finite element methods (FEM) also can be used for the analysis of the flow during injection and the behavior

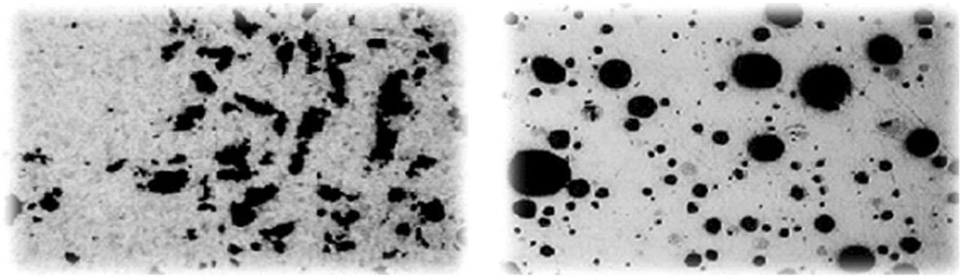

Fig. 2 Types of pores and their origins: **a** pore generated in solidifying stage and **b** pore generated by trapped air during the injection flow [7]

during solidification. Both understanding are needed for predicting pores in products injected in aluminum, either by air trapped, or by pore shrink [6]. Simulation results focused on solidification can lead to a definition of the origin of the pore by contraction more accurately. Sholapurwalla and Mathier [18] carried out simulations of thermo physical solidifications derived from HPDC process. It was concluded that the presence of pores, mainly its location, has a greater propensity to act as a crack initiation site for injection molded aluminum alloys. Studies have shown that for AlSi9Cu3 alloy, porosity was the main cause of failure, as evidenced by the initiation and propagation of cracks of individual pores [21].

Computer simulations for flow analysis for feed channels in dies for HPDC process and for analysis of solidification are centered, basically, in the download of geometric model, applying mesh, setting the alloy to be injected, first phase velocity, second phase velocity and the average temperature of the die. The results presented from simulations assist and enable a better understanding of the behavior and origin of the mechanisms of generations of possible defects on the HPDC process. To prevent casting defects, reducing production time and rework costs, it is important to develop a list of boundary conditions with data reliability [23].

The Magma CAE software, with specific application to HPDC aluminum process, uses FEM as a basis of calculation to solve flow and solidification problems of this complex process made up of many variables. It is an efficient tool to simulate the behavior of the injection and solidification of the product, besides being able to display different and reliable results, such as, the filling, distribution velocity, fill time, air entrapment during the solidification and verification of the mass concentration excesses [23].

Magma CAE software is premised on a fixed volume of control of the fluid to be analyzed, to enable the study of the flow behavior, vector velocity distribution, filling time, temperature distribution during the filling, the percentage of trapped air, behavior during solidification and the temperature distribution during solidification [7].

As discussed before, the porosity in HPDC process has always been a recurrent problem. With the increasing necessity for new designs with increased complexity for molded parts practically turned impossible completely eliminate the porosity, although the casting parameters and optimization techniques may limit them to acceptable size and areas. To understand the mechanism formation of porosity in aluminum casted alloys is of great interest to the industry because the porosity is not only the cause of degraded mechanical properties of the products but also has a negative effect on the machinability and surface properties [20].

The presence of porosity in HPDC process is accompanied by a reduction of the mechanical properties of the product, rejection when it is required secondary machining process and an aesthetic possible rejection. It is not only the percentage of total pore volume that influences the reduction of the properties but also the size, shape and position of the pores play an important role. With more porosity lower will be the density of the product through the voids occupying the total volume of the molded part, acting as a possible stress concentrators, thus increasing the probability of cracks and fractures. Furthermore, based on principles of fracture mechanism, the pore size is as important as the total amount of porosity [1]. Figure 2a shows pores with irregular geometry presenting its origin and definition as a pore of contraction and Fig. 2b shows rounder pore geometry and has its source and definition as of trapped air—derived from injection flow [11].

Typically the porosity is initially generated during aluminum contraction due to solidification or by trapping air taken into the cavity during the injection flow [5]. There are various possible causes and sources of pores, among them, we can mention the air displacement during the injection, die design, trapped air, air outlets, feeding channels, solidification behavior, lubricant on the piston injection bushing and quantity of water steam formation during the process. According to Vinarcik [22], the percentage of total porosity can be described by the total number of pores developed during solidification plus the amount of pores generated by trapped air, Eq. 1:

$$\%P = \frac{\beta V^*}{V_v} + \left(\propto \frac{T\rho L}{(237K)P} \right)(\upsilon - \upsilon^*) \tag{1}$$

where $\%P$ is the percentage of porosity; β is the shrinkage perceptual factor during solidification; V^* is the injected volume of liquid aluminum in the cavity in cm^3; V_v is the

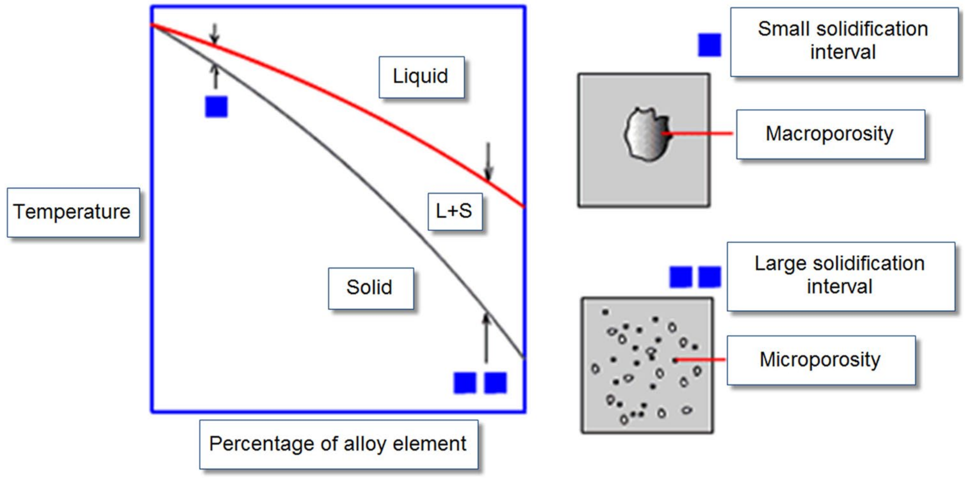

Fig. 3 Effect of interval solidification during contraction [4]

cavity volume in cm^3; $\propto$ is the fraction of air in the product; T is the gas temperature in the casting cavity in Kelvin; ρ is the density of the alloy in the melting temperature in g-cm^3; L is the length of the piece of aluminum; υ is the amount of gas contained in the injected part to 273 K temperature and 1 atm to 100 g of alloy; υ^* is the solubility limit of the gas temperature to 273 K and 1 atm to 100 g of alloy.

In the first part of Eq. 1, the pore is described in relation to the contraction during solidification and the second part of the equation describes the porosity due to air entrapment during the injection flow. Fractured surfaces in AE425 aluminum alloys were obtained at 300 °C and an investigation of the correlation of the porosity with the fatigue life of these casting alloys was made. It was found that 88% of all the examined samples had a tendency to fracture as a result of the porosity of the surface acting as the main responsible for crack initiation [2].

Porosity generated by contraction during solidification may be classified as macroporosity or microporosity. What determines whether it is a portion of the macro or micro type is the solidification range. The macroporosity can be a result of inadequate feeding often resulting from wrong mold filling, channel design with insufficient material flow, velocity, turbulence or even injection in the wrong place. This generated defect is known as pore by trapped air. The microporosity can be the result of the aluminum solidification condition and is often generated in product as a function of the excess of thickness, bags placed in the wrong location or even the mold with insufficient cooling. This defect is known as pore by contraction. During the aluminum transformation of liquid to solid occurs a packing of atoms forming a kind of ordered structures. In most cases, this transformation is accompanied by an increase in density and, consequently, a contraction. In alloys with small solidification interval they can show small dendrites on the interface, defined as liquid–solid (L–S) and tending to generate macro-porosities. The exception is aluminum alloys that despite having small dendrites, has large shrinkage during solidification. The metal alloys with wide range of solidification, as is the case with some brass alloys, present large dendrites in L–S interface and tend to generate microporosity. The microporosity is a defect which is characterized by its small size and distribution throughout the molded part. This type of pore is formed when the dendrites present in the solidification front, L–S interface, are of large scale. The microporosity also occurs due to the difficulty of liquid metal penetration between the dendrites in the L–S interface with the pressure drop, and as the local contractions are not compensated, porosity appears between the arms of the dendrites. The action to avoid such portion is the increase of the heat extraction in the die—enhancing die cooling circuits. Instead of the porosity become trapped at its source, the aluminum alloy can move the porosity forward solidification, leading all contraction and gas pores for a more central location, which highlights the importance of implementing the bags location [10], (Fig. 3).

The macroporosity characterized by contraction can be concentrated in a single point of the sample located at the last region to solidify—resulting in a void space and with rough internal surface formed by the dendrites. The shape and location of macroporosity depend on heat dissipation of the injection molding die. A form to control and change the solidification is to include bags in strategic regions of the product, this feature can be achieved accurately with the aid of simulations. The bags after injection of the pieces can be deburred and reused for a new injection cycle, minimizing the cost losses of the metallurgical process.

In many instances, the literature will correlate the source of porosity with cooling of the die. The temperature gradient in the injected joint is represented by the temperature difference between the aluminum and the die and can reflect the quantity, location, and also the percentage of porosity. The porosity generated during aluminum injection may also be caused by turbulence in the feed channel, i.e., the bubbling of hydrogen from a liquid solution or by contraction during solidification, although usually is a results of both effects [1]. The probability of porosity generation decreases with the increase of injection pressure. However, it may increase with excessive velocity during the injection flow in the feeding channel—increased probability of flow turbulence. Low volume occupancy rate in the injection bushing and sudden changes in feeding channel geometry can also generate possible turbulence. If these parameters are not adequately controlled pores can be generated [3].

The pressure drop, flow path, turbulence and variations in the geometry of the flow path, help and accelerate the pressure loss in feed channel—loss of efficiency of the feed channel. The pressure drop applied to molds can be defined as a form of energy dissipation during the aluminum injection flow. This pressure loss occurs mainly due to the channel path changes, as well as, product geometry changes since the steel surface of the die is polished, and the coefficient of friction is negligible. The pressure drop that occurs along the feed channel is called distributed call loss, while losses inside the volume are called localized loss. The flow is analyzed just inside the feed channel and its load loss is negligible. Thus, the expression of Bernoulli can be applied directly, Eq. 2.

$$\left(P_c + \rho \times \frac{\overline{V}c^2}{2} + \rho \times g \times z_c\right) - \left(P_b + \rho \times \frac{\overline{V}_b^2}{2} + \rho \times g \times z_b\right) = \left(f \times \frac{L}{D} \times \frac{\overline{V_c}^2}{2}\right) \tag{2}$$

where: P_c is the pressure supply channel, ρ is the density, $\overline{V}c$ is the velocity channel, g is the gravity, z_c is the channel height, P_b is the pressure bushing injection, $\overline{V}_b$ is the velocity bushing injection, z_b is the bushing injection height, f is the friction factor in the matrix, L is the channel length and D is the hydraulic diameter of the channel.

It must be remembered that this equation does not consider the friction between the fluid and the surface of the injection die. The application of this equation is not enough to calculate the pressure loss. For analysis and resolution of the pressure drop problems should be included two terms on the right side of this equation. These two factors are almost always calculated experimentally, so that the values found in a literature are not exactly the same. To determine the friction coefficient is required to characterize the fluid behavior in the section to be studied, i.e., to determine if the injection flow setting is laminar or turbulent. The flow behavior is defined by a ratio of magnitudes between the inertial and viscous forces—dimensionless Reynolds number, Eq. 3.

$$R_e = \frac{\rho \times V \times D}{\mu} \tag{3}$$

where R_e is the Reynold number; ρ is the density, V is the velocity channel, D is the hydraulic diameter of the channel and μ is the viscosity.

Thus, due to the injection flow during the cavity filling, we can say that the pressure loss in a feed channel of an injection mold, is a sum of pressure losses, i.e., the turbulence in the channels when the channel has excess of velocity or by the differences in feeding channel paths or changes in the flow depending on the geometry of the desired product.

The best strategy to reduce the porosity derived from the contraction is maximizing the product feed section and inject in such a way that the aluminum flow fills the largest possible area of the product at the same moment. It is also important always to prevent the occurrence of flow meeting, especially in split channels, since this flow division could generate possible turbulence in the cavity, i.e., non-simultaneous filling with high possibility of amendments in the final product. The product feed sections to be injected should be designed within the minimum necessary conditions of the process favoring the filling efficiency of the mold—reducing the probability of porosity generation. Gains are also obtained in a well designed channel feeding especially for velocity as low as possible—as the steel erosion wear is minimized.

The air when arrested while the cavity is filled may also result in products with pores. If the filling model is too complex, the metal will undergo turbulence during the flow—the erratic behavior transport air to the cavity. To avoid air entrapment in the die should be foreseen during the design, through computer simulations or through experience, bags and air vents in the most complex locations of filling, especially with meeting flow. Therefore, it is recommended to make a preliminary simulation, simply to define the location of the bags and after that definition, run the final simulation.

The air trapping is a dynamic problem during channel flow feeding and the hydrogen contraction is a problem of heat exchange in the process [6]. Therefore, it is important to state that during solidification air entrapment and aluminum contraction are the main sources of porosity. It is important to note that the correction in the feeding channel geometry can result in a lower percentage of air trapping with direct influence on the product pore percentage. In some cases, the porosity can be a result of the combination of trapped air and the failure in solidification and the amount of pores may also vary according to the amount of hydrogen in the aluminum injection process [1]. Nooruddin et al. [15] reported the study of the origin of the pore due to air entrapment. In the study 80% of the data were the

Fig. 4 High-pressure aluminum die casting machine

Table 1 Injection parameters

Liquid metal temperature (°C)	723
Mold temperature (°C)	288
First phase velocity (m/s)	Variable
Second phase velocity (m/s)	Variable
Injection pressure (Bar)	734
Piston stroke (mm)	250

results of simulations and 20% of the experimental data. In many practical situations the porosity generated by the evaporation cannot be found by FEM since this phenomenon is derived from the desmolding agent, water and oil leaks applied to the surface of the die–lubricating used on the bushing tip of the injection piston (NADCA [14].

In resume, it can be concluded, via the practical point of view, that it is more interesting to minimize the trajectory of the feed channel. However, is strongly recommended include air bags in the process. The bags can be interpreted as the extension of the injected product and are fundamental to prevent porosity by contraction. In solidification, it is always recommended to apply the bags at the end or at the meeting flow point—mainly in products that require multiple feeding areas. Eliminate the porosity caused by the contraction is practically impossible but is possible to minimize through a good mold design or by manipulating the injection process variables [11].

3 Methodology and experimental planning

To carry out this study it was chosen the main controllable and measurable process variables of the HPDC process, i.e., the first and second phase velocities, velocity of attack, fill time, solidification time and porosity. These velocities defined as boundary conditions were configured directly on the injection machine, Fig. 4. As the injection pressure results from the bushing piston diameter—the diameter of the bushing piston results from the ideal volume occupancy rate—it was defined for this study as a constant parameter. The volume occupancy rate depends on the volume required for each injection cycle, therefore the sum of the volumes of product, channels and bags. Experimentally it is recommended volumetric occupying rate between 40 and 60% of the available volume in the injection bushing.

To perform the analysis using X-ray it was produced 27 samples for all the boundary conditions. It was carried out the casting of 10 kg of SAE 306 alloy in an electric induction furnace—Inductotherme type—with power of 250 kW. The charge was melted at the temperature of 760 °C to compensate for heat loss during the process of degassing and displacement of the charge till the furnace. The time required to reach the handling temperature was around 30 min. The material was transferred to the transport crucible for degassing by bubbling in nitrogen for 10 min. After removal of the dross concentrated in the crucible surface, the material was transported by a truck to the auto-dosimeter oven of the injection machine. To produce the samples, it was used a Colosio 550T injection machine. The injection cell was composed by auto-dosimeter oven, injection machine and robot to remove the product from the mold, cooling tank and aluminum deburring system. The full injection processing cell was automated leaving to the operator only the supervision task.

The injection cycle started with the automatic dosing by the furnace of the aluminum charge that was injected into the injection bushing. During the aluminum injection the product solidifies and the injection machine and mold was opened to allow the removal of the product from the mold by the robot. During this process, it was necessary the application of a mold release agent using a mechanism at the top of the injection machine. This whole process was carried out in an automated cycle of 80 s. Table 1 presents the injection parameters used to produce the samples and Table 2 shows the chemical composition of the aluminum 306 alloy.

To study the influence of the first and second stage velocities in the pore generation, a combination of boundary conditions was required, both from the simulation and during the experimental processing. Table 3 shows all boundary conditions for validation of the simulation results. By the combination of boundary conditions it was possible to measure and understand the behavior of porosity.

After the experimental tests the simulations with the same process conditions were performed (validation). For the numerical simulation it was used the Magma, Click-2cast and Jump softwares. Table 4 presents the values of

Table 2 Chemical composition of aluminum alloy SAE 306 ($AlSi^9Cu^3$)

Element	Si	Cu	Mn	Mg	Fe	Zn	Ni	Al
wt%	9.5	3.0	0.4	0.5	0.9	1.0	0.3	Balance

Table 3 Boundary conditions for injection: Vp% is percentage of the velocity of the first stage, Vp is first stage velocity in m/s, Vs% is percentage of the velocity of the second stage, Vs is second phase velocity in m/s

Hypothesis	% Vp	Vp (m/s)	% Vs	Vs (m/s)
1	15	0.03	5	0.58
2	15	0.03	50	3.57
3	15	0.03	99	4.20
4	50	0.26	5	0.58
5	50	0.27	50	3.20
6	50	0.26	99	4.01
7	99	0.28	5	0.82
8	99	0.28	50	2.81
9	99	0.29	99	3.15

velocities in the attack channel obtained with the simulated feed channel compared to the channel velocities obtained in the Colosio 550T injection machine. The percentages defined for the first and second velocity stage were defined from the minimum required values to a visual approval. In the case of the first phase velocity, it was impossible to obtain physical samples with conditions of filling below 15%. The injection pressure was adopted constant of 724 bar. To understand the influence of the injection process variables in the porosity the filling time, velocity in the feeder channel, solidification time and porosity were simulated.

The velocity in the attack channel in the cavity feed section should be about a maximum value of 40 m/s. Practical experience shows that values higher than this greatly increase the probability of wear in the die—erosion resulting from the injection flow. Excessive attack velocity can generate problems, such as, early cracks in the die that can accelerate the thermal fatigue. For velocities above the recommended, it is known that the energy applied to the die from the injection flow shock, results in a considerable increase in heat concentration, thereby significantly reducing the steel hardness—increasing the generation of cracks.

The x-ray nondestructive analysis was performed using three samples injected for each hypothesis. To do this, it was used a digital fluoroscopy image capture system using a Radioscopic Inspection System DP 432.158HP equipment. The objective was to get the actual levels of pores of each proposed combination and thus compare them to the obtained simulations data.

4 Results and discussion

Table 4 shows the numerical simulations results for the studied parameters obtained with the Magma and Click-2cast softwares. The highlighted value would be closer to the recommended one but, analyzing the flow and the die life, it is not the most efficient result for the minimum amount of obtained porosity. The analysis of the fill time shows that the best velocities applied are those who can fill the cavity in a shortest possible time. In this case, the lowest possible times were obtained when the velocities of both first and the second phase were maximum. But high velocities can also result in porosity because higher

Table 4 Results of numerical simulations

Controlled process variables		Measured process variables			
Velocity 1st phase (m/s)	Velocity 2nd phase (m/s)	Velocity in attack (m/s)	Fill time (s)	Solidification time (s)	Porosity (m^3)
0.03	0.58	11.282	4.4249	13.879	6.8269e−06
0.03	3.57	86.106	4.2956	2.9293	6.8612e−06
0.03	4.20	101.16	4.2725	3.5075	9.7893e−06
0.26	0.58	22.687	0.4909	2.7271	9.6775e−06
0.27	3.20	81.354	0.4973	2.4435	6.8975e−07
0.26	4.01	101.19	0.5114	2.4876	1.0113e−05
0.28	0.82	14.832	0.4814	2.6421	9.1557e−06
0.28	2.81	56.622	0.4842	2.5072	7.1241e−06
0.29	3.15	42.855	0.4674	2.4983	1.0130e−05

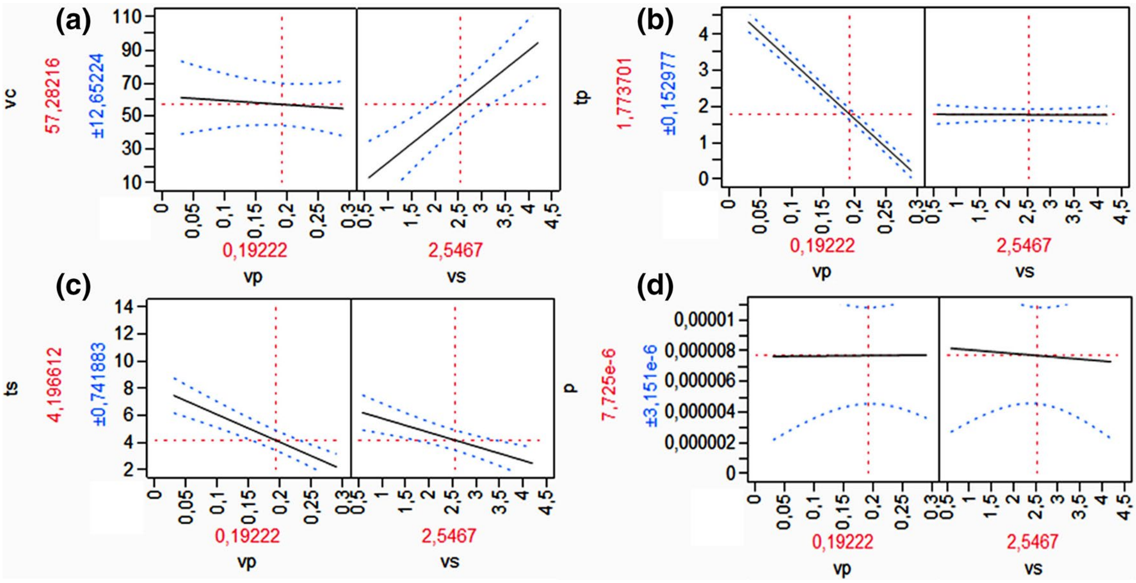

Fig. 5 **a** Channel velocity (m/s) as a function of the first phase velocity (m/s) and second phase velocity (m/s); **b** Fill Time (s) as a function of the first phase velocity (m/s) and second phase velocity (m/s); **c** Solidification time (s) as a function of the first phase velocity (m/s) and second phase velocity (m/s); **d** Porosity (m^3) as a function of the first phase velocity (m/s) and second phase velocity (m/s)

turbulence can produce trapped air much more easily. Thus, it can be concluded that the fill time does not influence the generation or elimination of pore volume. Practically, it is also desired the solidification time smallest as possible. This is because, in addition to maximizing the productivity of HPDC process, the shorter time decreases the temperature gradient in the mold.

From the obtained numerical simulations results was developed the statistical model for the channel velocity. The proposed statistical model was obtained using the method of least squares—based in the equation depending on the first and second phase velocities, *vc*, *tp*, *ts* and *p*. The following equations were obtained by Jump software.

$$f(\alpha_1, \alpha_2, \ldots \alpha_n) = \sum_{k=1}^{m} \left[f(x_k) - \phi(x_k)\right]^2 = \sum_{k=1}^{m} \left[f(x_k) - \alpha_1 g_1(x_k) - \alpha_2 g_2(x_k) - \ldots - \alpha_n g_n(x_k)\right]^2 \quad (4)$$

where, $vc = f(vp, vs)$, $tp = f(vp, vs)$, $ts = f(vp, vs)$, $p = f(vp, vs)$, $p = f(vp, vs, vc, tp, ts)$ and the statistical model final equations for the channel velocity, fill time, solidification time, porosity are presented below:

$$vc = 4.95038 - 25.38529 \times vp + 22.46489 \times vs + (vp - 0.19222) \times ((vs - 2.54666) \times -15.21915) \quad (5)$$

$$tp = 4.81097 - 15.73427 \times vp - 0.00503 \times vs + (vp - 0.19222) \times ((vs - 2.54666) \times 0.22267) \quad (6)$$

$$ts = 10.72902 - 20.30011 \times vp - 1.03283 \times vs + (vp - 0.19222) \times ((vs - 2.54666) \times 12.78965) \quad (7)$$

$$p = 0,000000082810 + 0.00000032904 \times vp - 2.43046e - 7 \times vs + (vp - 0.19222) \times (vs - 2.54666) \times (-0.00000049995) \quad (8)$$

Figure 5 shows the overall behavior of the process. It can be observed, the channel velocity variation as a function of the first and second phase velocities. It is evident the influence of the second phase velocity in the channel variation velocity, i.e., in the section where the product are fed into the mold cavity, Fig. 5a. Figure 5b illustrates the fill time behavior as a function of the first and second phase velocities. Unlike velocity in the channel, the filling time is dependent on the first phase velocity and for the second phase velocity the filling time shows more stable behavior. After the analysis of the results obtained through the simulations it was concluded that there is no direct relationship with the velocities of first and second phase with the solidification time, Fig. 5c. But it was concluded that the lower the solidification time, the lower the pore volume in injected aluminum product. Figure 5d shows the porosity

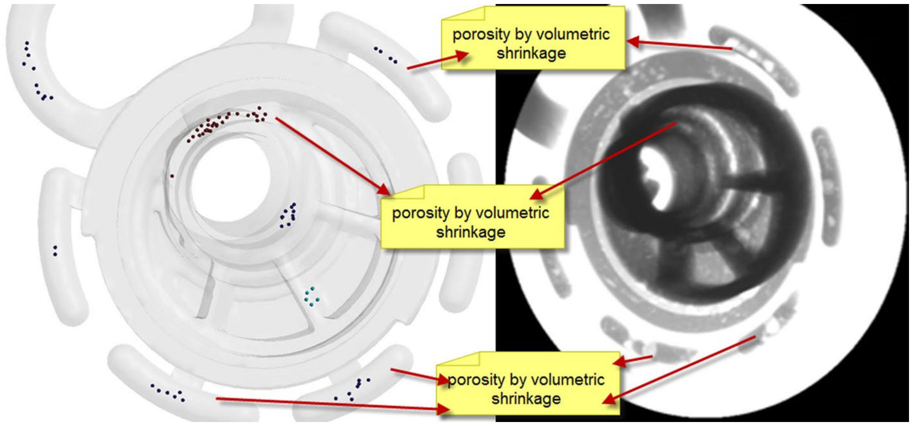

Fig. 6 Porosities of 15% resulting of the first phase velocity and 5% resulting of the second velocity phase: **a** obtained through simulation and **b** obtained by the X-ray

as a function of the first and second phase velocities. The lowest solidification time of 2.4435 s promoted a volume of porosity of 6.8975e−07 m^3. Therefore, it highlights the importance of refrigeration systems in molds for HPDC process that, besides to improve process efficiency and productivity, helps to stabilize the temperature of the mold and, consequently, minimizing the amount of porosity generated through the process.

The x-ray nondestructive analysis shows that the first and second phase velocities are not directly responsible for the origin and generation of porosity in aluminum molded parts through the HPDC process. The combination of the velocities directly affects only the velocity in the feed channel and the filling time, Fig. 6.

From the data of Table 4 and with the overall picture of the results a general mathematical equation of the behavior and origin of porosity in HPDC process obtained by JUMP software is presented. This general equation is represented as a function of the variable first and second phase velocities, channel velocity, fill time and solidification time $p = f$ (vp, vs, vc, tp, ts, tm, ta). The general equation of porosity may be more complete when applying the variables mold temperature—ranging from 250 to 260 °C—and also with the temperature of the injected aluminum ranging from 690 to 700 °C.

$$\begin{aligned} p = {} & -0.0011117 - 0.000082125 \times \left(\frac{(vp - 0.16)}{0.13}\right) \\ & + 0.000012430 \times \left(\frac{(vs - 2.39)}{1.81}\right) - 0.00001615 \\ & \times \left(\frac{(vc - 56.236)}{44.954}\right) - 0.000072705 \times \left(\frac{(tp - 2.44615)}{1.97875}\right) \\ & - 0.0000007403 \times \left(\frac{(ts - 8.16125)}{5.71775}\right) + 0.00000020990 \\ & \times tm + 0.000001523 \times ta + \left(\frac{(vs - 2.39)}{1.81}\right) \\ & \times \left(\left(\left(\frac{vc - 56.236}{44.954}\right)\right) \times 0.000002663\right) + (tm - 255.44444) \end{aligned} \tag{9}$$

5 Conclusion

This research brings scientific and practical value to the injection segment in aluminum under-pressure process with a direct interest by the academic field, but also with interest of aluminum casting companies through the high-pressure aluminum die casting process (HPDC). Mapping the source of the error-and-solutions for the elimination of the pores allows a global economy when there is correction of this recurrent problem. When the trend can be detected during the simulation process, it is possible to correct the mold prior construction. The main contribution of this work was to verify with the help of simulation software—and validated by X-ray analysis—that the solidification time can be the main source of origin of porosity in HPDC process. Numerical simulations using Magma and Click2cast softwares have been quite helpful; mainly the result obtained from the post-processing related to the trapped air, i.e., it was possible to correlate the percentage of trapped air with the amount of pores according to the ASTM standard. This research can permit the link of the theoretical relationship with the practice of the HPDC process. The proposed methodology using numerical simulation, supported by bibliographic concepts, can allow the post-processing simulation data interpretation validated with experimental testing. The proposed general mathematical equation can be very helpful to the determination of the probability of occurrence of pores in the product during injection process.

Acknowledgements This research was supported by Federal University of Paraná (UFPR). The authors gratefully extend their gratitude to Metalkraft injection Ltda for the numerical simulations in Magma software, Metallurgical Starcast Ltda by providing the mold and the injection of the test samples and Alumec Industry Ltda by the of X-ray analysis.

References

1. Aminul I, Zoheir NF (2011) The influence of porosity and hot isostatic pressing treatment on wear characteristics of cast and

P/M aluminum alloys. Department of Process Engineering and Applied Science, Materials Engineering Program, Dalhousie University, Halifax
2. Ammar HR, Samuel AM, Samuel FH (2008) Porosity and the fatigue behavior of hypoeutectic and hypereutectic aluminum-silicon casting alloys. In: International Journal of Fatigue, Département des Sciences Appliquées, vol 30, Université, Chicoutimi, Québec, pp 1024–1035
3. Campatelli G, Scippa A (2011) A heuristic approach to meet geometric tolerance in high pressure die casting. Department of Mechanical Engineering and Industrial Technologies, University of Firenze, Firenze
4. CIMM (2016) http://www.cimm.com.br/portal/material_didatico/3686-microporosidade#.V4z GgMvrs08, Brasil
5. Hangai Y, Kitahara S (2008) Quantitative evaluation of porosity in aluminum die castings by fractal analysis of perimeter. Mater Trans 49(4):782–786 **(Japan, 2008)**
6. Irfan M, Schwam D, Karve A, Ryder R (2010) Improvements of Mechanical Properties in Die Cast Engine Blocks. In: 114th Metalcasting Congress, FL: North American Die Casting Assocation, Orlando, EUA
7. Jakumeit J, Jana S, Böttger B, Laqua R, Jouani M, Bührig-Polaczek D (2011) Simulation-based prediction of micro-shrinkage porosity in aluminum casting: Fully-coupled numerical calculation vs. criteria functions. In: The 3rd International Conference on Advances in Solidification Processes, Germany
8. Jin CK, Kang CG (2011) Fabrication by vacuum die casting and simulation of aluminum bipolar plates with micro-channels on both sides for proton exchange membrane (PEM) fuel cells, Precision Manufacturing System Division, Graduate School, Pusan National University, San 30 Chang Jun-dong, Geum Jung-Gu, Busan 609–735. In: Engineering Research Center for Net Shape and Die Manufacturing, School of Mechanical Engineering, Pusan National University, San 30 Jangjeon-dong, Geumjeon-gu, Busan, pp 609–735
9. Johnson A (2012) An Investigation of Internal Logistics of a Lean Bus Assembly System via Simulation: a Case Study. In: The international journal of industrial engineering is abstracted by thomson reuters science citation index, engineering index/compendex, eipage1, and current contents e engineering, computing and technology, New York, EUA
10. Jorstad J, Pan Q, Apelian D (2007) Interaction of key variables during rheocasting: effects of fraction solid and flow velocity on performance. In: 111th Metalcasting Congress. Houston, TX: North American Die Casting Association, EUA
11. Kirkman S (2006) Shrinkage porosity: a guide to correcting the problems. North American Die Casting Association, EUA, Wheeling
12. Klobcar D, Tusek J, Taljat B (2007) Thermal Fatigue of Materials for DieCasting Tooling, University of Ljubljana, Faculty of Mechanical Engineering. Materials Technology Department, Slovenia
13. Miller R (2010) An Extension to PQ analysis: selecting die and machine to quantitatively maximize operating flexibility. Cast-Expo'10, FL: North American Die Casting Association, Orlando, EUA
14. North American Die Casting Association, Die Materials & Technologies. (2011). Wheeling, IL: North American Die Casting Association, EUA
15. Nooruddin AH, Anifowose F, Abdulraheem A (2014) Using soft computing techniques to predict corrected air permeability using thomeer parameters, air porosity and grain density. In: Computers & Geosciences, King Fahd University of Petroleum and Minerals, vol 64, Dhahran, pp 9–80
16. Proske M, Gaddam D (2009) Autonomous Optimization: Determining the Process Window before Casting the First Part. In: Die Casting Engineer, North American Die Casting Assn, Die Casting Engineer; 53, 3; 22–25, EUA
17. Sakundarini N (2012) A framework of integrated recyclability tools for automobile design. In: The International Journal of Industrial Engineering, International Journal of Industrial Engineering, vol. 19 Issue 10, pp 401–411 **(11p)**
18. Sholapurwalla S, Mathier V (2010) Optimizing the High pressure die casting process using computer simulation; *Cast-Expo'10*. North American Die Casting Association, EUA
19. Steedman G, Bishop DP, Caleyw F, Kipouros GJ (2012) Surface porosity investigation of aluminum-silicon PM alloys. In: Materials Engineering Program, Department of Process Engineering and Applied Science, Dalhousie University, 1459 Oxford Street, Halifax
20. Tsoukalas VD (2008) Optimization of porosity formation in $AlSi_9Cu_3$ pressure die castings using genetic algorithm analysis. In: Materials and Design, Department of Marine Engineering, Athens Merchant Marine Academy, Paralia Aspropyrgou 19300, Aspropyrgos, Athens
21. Vanderesse N, Maire E, Chabod A, Buffière J (2011) Microtomographic study and finite element analysis of the porosity harmfulness in a cast aluminium alloy. In: International Journal of Fatigue, Université de Lyon, INSA-Lyon, MATEIS CNRS UMR 5510, 69621 Villeurbanne, Centre Technique des Industries de la Fonderie (CTIF), vol 33, France, pp 1514–1525
22. Vinarcik EJ (2002) High integrity die casting processes, Wiley, Hoboken, Includes index, ISBN 0-471-20131-6, die-casting. I. Title. TS239.V56 671.2 53 dc21, Canada
23. Wannarumon S, Actis M (2009) Comparisons of computer fluid dynamic software programs applied to jewelry investment casting process. In: World Academy of Science, Engineering and Technology 55, EUA