

## INTENSIFICATION PRESSURE IN DIE CASTING

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### ABSTRACT

The pressure is increased at the end of the die cavity filling, and it is referred to as the intensification (pressure). Many have attempted to solve the problem: What is the required pressure? Yet, there is no a single article that has a successful (even reasonable) answer or model so the process can be understood and a determination what is the minimum ideal pressure. The strange idea that the numerical simulations without getting the physics involve can produce any advance is very common in the field. The numerical works have never produce any substantive solution without a real physics input, in other words: no solution was produced. Thus, experimental techniques were employed.

So, it is a typical practice in die casting to use statistical analysis or a case study where arbitrary values experimentally are employed. Every time the term statistical study is used, it is a code name to mean that “we have no clue what is going on”. The study of minimum ideal required intensification pressure has only case of experimental study or random value of pressure is used. Generally, it has been assumed that the intensification should be done to compensate for the shrinkage porosity and/or entrapment porosity without knowing the actual value to which the intensification should be increased. In fact, there are numerous poorly done research attempts to experimentally study the relationship between the intensification pressure and the properties of the cast material. Of course these attempts did not provide any meaningful idea.

The current study is done from a physical point of view based on physical reasoning plus with analytical approach. This analysis provides a solution (or maybe even the solution) for the minimum ideal pressure. For the first time, the relation between the casted material and the operational requirement is provided.

### NOMENCLATURE

$B_T$  Bulk modulus  
 $E$  Young's modulus  
 $P$  Pressure  
 $T$  Temperature  
 $V$  Mold plus the extra volume  
 $\Delta V$  Shrinkage volume

#### Greek Letters

$\alpha_v$  expansion coefficient  
 $\nu$  Poisson ratio  
 $\rho$  Density

#### Subscript

$e$  room temperature  
 $L$  liquidus temperature  
 $m$  injected temperature  
 $m_1$  upper mushy zone temperature  
 $m_2$  the lower mushy zone temperature  
 $mushy$  the mushy zone  
 $s$  solid zone

### Key Words

Die Casting Process, Intensification pressure, Die casting process

### 1 Introduction

The die casting process had several open questions which four/five of them were solved by this author. These open questions include: 1) vent size, 2) gate size 3) critical plunger velocity, 4)  $pQ^2$ , 5) Optimum/Actual cost, 6) vent location/number, 7) gate velocity, 8) runner design, 9) filling time, and 10) intensification pressure (Bar-Meir and Brauner 1999). Some of these open questions were solved completely (1,3,5, and 8) and some

partially by this author and his associates (2, 4, 5, 7, and 8) . Of course, there are also made up open questions such porosity due to the hydrogen release for the purpose of gain grant money. In this discussion, another of these open questions finally is tackled.

A major problem in die casting is the porosity. The contribution that make all these advances has to be attributed to Eckert (1989) to his ground breaking work<sup>1</sup>. The porosity is divided by the causes that create it. Generally two main categories are one) the shrinkage porosity and two) the entrapment porosity. The solutions to these two different causes are mostly different with the exception of the increase of the pressure in the cavity (the intensification). Until this paper, there was no idea how to deal with shrinkage porosity. The only understanding was that the pressure has be increased without the ability to quantify the amount or even the mechanism to help calculate it. The only instinct or intuition was that pressure needs to be increased. To find how much the pressure has increased, many studies were done mostly by experiments (actual or numerical). For example, Karban (2000) studied the intensification and gate velocity etc by experimental means. There no shred of information that sheds a light on die casting process and/or that is useful in that dissertation. For example, there is no mentioning of the critical vent area, no idea what is the critical plunger velocity etc to determine where the data fit. The point of bringing the attention to this work is to demonstrate that while a lot money was spent on research, no serious research was done.

The entrapment porosity to a large extent is solved (Bar-Meir 2021b). The critical gas venting area was formulated and found for example when the mold is exposed to the atmosphere (Bar-Meir, Eckert, and Goldstein 1997) or for vacuum system (Bar-Meir, Eckert, and Goldstein 1996). From these two works, it pretty much can be determined when to use vacuum assist is needed. The complicate solution of replacing the gases with oxygen and then having the oxygen diminished by the reaction was solved again by this author (Bar-Meir 1995a). Even the minimum size of the vacuum consideration was investigated (Bar-Meir, Eckert, and Goldstein 1999) and the problem should be considered solved with the exception of the location and the number vents and gates. Another major source of entrapment is the shot sleeve where hundreds of teams have tried to solve in vain to solve the problem. Here are examples of these poor attempts to solve the plunger critical velocity (Kohlstädt, Vynnycky, Goeke, and Gebauer-Teichmann 2021; Gunasegaram, Givord, O'Donnell, and Fennin 2013; Faura, López, and Hernández 2001; Gašpár, Paško, Malik, Panda, Jurko, and Mašđenik 2012; Lea 1982; Chava, Falcone, and Teodoriu 2008; El Mehtedi, Mancia, Buonadonna, Guzzini,

Santini, and Forcellese 2020). Again it was solved in the paper (Bar-Meir and Brauner 2021). Additionally another source is gas entrapment in the runner or runner design which will be published in the next version of the “Fundamentals of Die Casting Design”. Again the only issue is the locations and the number of the vents and gates is still opened question. Some guidelines are provided, while this author consider this issue still open, Yet, this topic does not seem going to be solved any time soon and probably will have to wait for the next generation. Note that all numerical works, so far, have not produced any tangible information on any part of the die casting process. See for another example (Wang, Huang, Fu, Yu, and Yao 2022), a work that put into question the whole research (Crowley 2021).

Kohlstädt et al (2021) provide an excellent example how to spend large amount of efforts and yet getting useless information at the end. In the word “useful information” it means something tangible and a die casters somewhere can use. Kohlstädt used the turbulence model in domain where there is no turbulence like a still liquid metal which violated the first and second laws of thermodynamics. The reason that this assumption violates the thermo’s laws is that in a still liquid there is no kinetic energy to fuel the turbulence. This invented energy continue stirring the liquid metal maybe or it is only imaginary stirring. Yet, in the same time, the liquid metal has zero velocity at the wall (no slip condition) when the liquid is forced to move. Additionally, the pressure is not calculated but is assumed to have erroneous values. As these errors are not enough, there is no results but only specific case (which is wrong) and there is no path to expend it. This work should enter to Rube Goldberg machine competition and probably will win the first prize easily.

The main issue in any search is to find the mechanism(s) which affects the issue at hand. Here are examples of clueless research and reviews of the die casting. Adamane et al (2015) stated that “[a]lthough the design of vents and overflows in a die casting is rarely discussed in the literature, it constitutes an important die parameter that can influence the casting quality.” Only poor literature review can show no research while google scholar shows about 29,400 results. The solution of the critical vent area has been solved since 1995 (Bar-Meir 1995b). While one can observe the same poor quality as Adamane’s work appears in literature also such as (Wang 2007) because no one in world can reproduce this work due to missing important parameters. This fact of poor research does not mean that there are no breakthroughs work in the die casting. Bonollo et al (Bonollo, Gramegna, and Timelli 2015) reviews named as “contradictions and challenges” of the die casting without actually doing any real literature review. In way, Bonollo et al seems to be under the illusion that the intensification pressure should be only monitored.

The shrinkage porosity was approached by the “last place to fill” method. In this method, is a hope that somehow as the freezing occurs while the liquid metal continue to be fed to the mold. In this method it is assumed that as the liquid metal so-

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<sup>1</sup>In fact, one of indication of quality of work in die casting is examining whether the author familiar with Eckert’s paper.

lidified and shrinkage the liquid will be supplied to fill the gap. The problem in this method is that no one can predict this/these location(s). Furthermore, even if the location(s) was/were known it not possible to supply gate to that point. In fact, this author observed that if last location is known and somehow the feeding of that location is done, it will result in moving the last fill location. The icing on the top of all these problems, even if these locations miraculously solved, the fact remains find the location does not solve the problem. Regardless to the location the shrinkage porosity will continue as the last location does not prevent it.

### 1.1 Intensification Period

The two main concerns in this phase is to extract heat from the die and to solidify the liquid metal as raptly as possible to obtain the final shape. These statements made under the assumption that the rate of solidification does not affect the properties. Thus, two operational parameters are important: one) the (minimum) time for the intensification and two) the intensification pressure (and the clamping force). These two operational parameters can improve casting design to obtain a good product. In the literature there are papers dealing with this aspect. Perhaps of the typical misunderstanding can be expressed by the paper by (Adamane, Arnberg, Fiorese, Timelli, and Bonollo 2015). While they show the some of the phenomena in die casting they are not aware that all of their finding was discussed in the past. For example, their paper displays a plot depicting the effect of varying plunger velocity on the tensile properties. This data point is meaningless without providing percentage filled and other data.

The main resistance to the heat flow is in the die and the cooling liquid (oil or water based solution). In some parts of the process, the heat is transformed to the cooling liquid via the boiling mechanism. However, the characteristic of boiling heat transfer time to achieve a steady state is larger than the whole process and the typical equations (steady state) for the preferred situations (heat transfer only in the first mode) are not accurate. When there is very limited understanding of so many aspects of the process, the effects of each process on other processes are also cluttered. However, using dimensional analysis provides the lens to clarify the process.

In the current version of the die casting book (2021b), this point was connected the physics of the problem. It has been realized that the intensification pressure is to compensate for the shrinkage (Bar-Meir 1995b). Hence, after these elements were connected but even after this breakthrough several elements might require refinements.

Suppose the mold contains almost only liquid metal and a small amount of gases and it undergoes almost static solidification. The energy (movements) in liquid affects the liquid metal. While this point was not investigate thoroughly, the estimate shows that it is not significant (only a point of refinement) (Eckert 1989). The question in this discussion, what should be

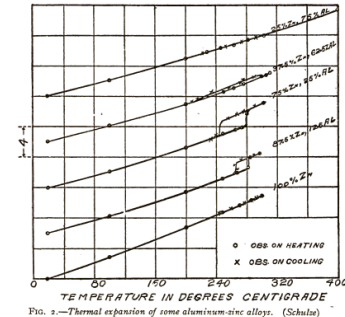


FIGURE 1. Thermal expansion of Aluminum After Hidnert 1925.

the intensification pressure should be overcome shrinkage ignoring the minor effects as the kinetic energy. In the process the liquid undergoes several temperature ranges for which the total change is the sum of its components. The total volume changes are made out of three different temperature zones: liquid, mushy, and solid (or maybe another mushy zone). The shrinkage from above the room temperature to the melting point is

$$\Delta V = V \alpha_{V_s} \Delta T \quad (1)$$

Symbol	Definition
$T$	Temperature
$V$	mold plus the extra volume
$\alpha_{V_s}$	the solid volumetric expansion

According to Blumm (2000) this coefficient is constant or close to it. At first approximation this recommendation is adapted here. Generally speaking, the expansion of liquid metal shows some hysteresis behavior (Hidnert 1925) and the cooling path has to be selected (less significant for a large temperature range). Furthermore, the reference is old and today work shows more linear behavior. However, some of the latest works put this author in an awkward position of not being able to be more deterministic as these works are conflicting and do not inspire confidence. Yet, with the above in mind, some average values can be used.

The purpose of the intensification is to compensate for the thermal shrinkage (and some of the other shrinkage). Thus, the thermal expansion needs to be equal to the mechanical contraction due to the pressure (by volumetric Hook's law). As the calculations of energies should be part of the analysis of the elastic system at hand based on various distortions of the body should be included when refinements are investigated. While the body in part of the temperature path goes in the liquid phase, the mushy zone, and solid phase all these contributions: stretching, shearing, bending, twisting cannot be accounted in a simple way. Thus, others are invited to improve this section. Additional point to consider is that cooling path in the liquid phase occur

under constant pressure and not under variable pressure. This effect is ignored because the mathematical complication and lack ability to quickly estimate it. The dimensional analysis not presented here hints that this change is less significant. For course, this analysis assumed that the result depends on the state and not the path (typical thermo assumption) which the author cannot completely justifies as there are possible residuals stress (which should be accounted for). It is hoped that these assumptions will be corrected in the future. Thus, as a first approximation it can be written that

$$\Delta V = V [\alpha_{vL}(T_m - T_L) + \alpha_{vmushy}(T_{m1} - T_{m2}) + \alpha_{vs}(T_{m2} - T_e)] \quad (2)$$

where the

$T$	temperature
$\Delta V$	Shrinkage volume
$V$	Volume
$\alpha_v$	Expansion coefficient
subscript	
$e$	Room temperature
$L$	Liquidus temperature
$m$	Injected temperature
$m_1$	Upper mushy zone temperature
$m_2$	Lower mushy zone temperature
$mushy$	Mushy zone
$s$	Solid zone

While the temperature change is applied to runner as well, the “transfer” of volume (material) from or to mold is minimal during the cooling process. The predicted shrinkage is based on the volume of the mold plus the vent system. The shrinkage and/or contraction are in a small range, the difference is neglected because the simplicity is paramount here. It can be noticed that in most cases, the flow, during the solidification, is from the runner system to the mold and from the mold to the venting system. Material that transferred from the runner to the mold put this estimate a bit in the over estimate range. While the transfer to the vent system put in the under estimate range. These two transfers, while not totally canceling each other, are conflicting and reducing the combined effect.

The contraction of the volume due to the pressure based on [Section 1.62 p. 24] (Bar-Meir 2021a)

$$B_T = -V \left( \frac{\partial P}{\partial V} \right)_T \quad (3)$$

The intensification process is to a large degree can be considered as isothermal since the amount of heat lost in the process

is relatively minimal and thus the temperature variation is small as well. While in theory the increase of the pressure can cause change in temperature which push liquid metal past the liquidus line. Hence, it is reasonable to assume the process is isothermal. This point is swelled because for some materials this assumption is not proper. The total change is

$$-\int_{P_1}^{P_2} \frac{\partial P}{B_T} = \int_V^{V-\Delta V} \frac{\partial V}{V} \quad (4)$$

which can be integrated as

$$-\frac{P_2 - P_1}{B_T} = \frac{\partial V}{V} \Big|_V^{V-\Delta V} = \ln \frac{V - \Delta V}{V} = \ln \left( 1 - \frac{\Delta V}{V} \right) \quad (5)$$

Rearranging eq. (5) yields

$$e^{\frac{P_1 - P_2}{B_T}} = \left( 1 - \frac{\Delta V}{V} \right) \quad (6)$$

or

$$\Delta V = V \left( 1 - e^{\frac{P_1 - P_2}{B_T}} \right) \quad (7)$$

Notice that the assumption of constant bulk modulus is very strong. However, it can be replaced by numerical integration for a specific material. As stated earlier, this point is only a refining point.

These two changes (mechanical and thermal) of volume should be about equal as

$$\mathbb{V} \left( 1 - e^{\frac{P_1 - P_2}{B_T}} \right) = \mathbb{V} [\alpha_{vL}(T_m - T_L) + \alpha_{vmushy}(T_{m1} - T_{m2}) + \alpha_{vs}(T_{m2} - T_e)] \quad (8)$$

It should be noted that a more precise way will be to consider the variations of the pressure on  $B_T$ . Again, the paramount in this poor man analysis is the simplicity. As the most fundamental and breakthrough models are normally the poor man analysis, the point here to extract the range of the ideal intensification pressure.

$$P_1 = P_2 + B_T \ln \left\{ 1 - [\alpha_{vL}(T_m - T_L) + \alpha_{vmushy}(T_{m1} - T_{m2}) + \alpha_{vs}(T_{m2} - T_e)] \right\} \quad (9)$$

In the derivations, some simplifications were made but yet the reasonable results which show the indication of the intensification required to reduce to zero the thermal shrinkage. It is interesting no one consider this mechanisms or other explanation to obtain the required intensification pressure. Another point for the solid the linear expansion can be used in case it is the unknown multiplied by the right coefficient (3).

The relationship between the Young's modulus or modulus of elasticity and the bulk modulus for linear and continuous material (no phase change) is

$$B_T = \frac{E}{3(1-2\nu)} \quad (10)$$

Symbol	Definition
$E$	Young's modulus
$\nu$	Poisson ratio

This relationship is adapted here and a refinement probably is required to deal with the phase change of various material. For example, the Poisson ratio is a function of the temperature where here is assumed constant. Hence, eq. (11) can be written in term of Young's modulus

$$P_1 = P_2 + \frac{E}{3(1-2\nu)} \ln \left\{ 1 - [\alpha_{VL}(T_m - T_L) + \alpha_{Vmushy}(T_{m1} - T_{m2}) + \alpha_{Vs}(T_{m2} - T_e)] \right\} \quad (11)$$

Note that Young's modulus should be taken at the value at liquid phase.

## Concluding Remarks

Here the relationship between the die, the die cast material and the intensification pressure was established. The presentation provides the framework on which the improved models for specific materials can be build. This paper is only preliminary examination of this topic. Yet, the intensification can be considered as a solved problem and only a refinement is needed.

## Acknowledgment

The foundation to this paper was seeded in the problem this author was dealing with frozen pipes in relation to the strength of material for the rain barrels. Apparently the problem is also manifested with car breaks and energy harvesting which cannot be discussed here and only acknowledged. These anonymous individuals (who want to be so) made several remarks which contribute to some of understanding of this problem.

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## About the Author

As opposed to many other researchers, this author does not brag about how many citations his work has or jobs he held but only points to how many breakthroughs he has made and on how many people plagiarized his work. In the die casting industry, he has revolutionized the field by solving several major open questions. These questions include the critical plunger velocity,  $pQ^2$  diagram, intensification pressure and critical vent area etc (for those who not familiar with die casting, these are the main pliers of die casting.). It has to be mentioned that the die casting establishment believed in solutions which violated the second law of the thermo and has spent millions promoting these beliefs (like the woke religion). Since the problems were not solved, literally hundreds of CFD teams from all over the world attempted to solve the problem in vain where this author solved them. The establishment fought against publishing these discoveries. The irony is that these author's models today are undisputed and accepted in the industry.

Furthermore, this servant solved several open problems in shock dynamics and potential of compressed substances. Additionally, this author solved the deep ocean pressure and speed of sound which many oceanographers failed to calculate (Pushka Equation).

Bar-Meir was instrumental in developments of the added mass (properties) concepts. He differentiate between the added properties and the transfer properties. He discovered the change of the added mass and it effects on the governing equations. He invented the stability dome for floating bodies and in the process developed the equation for centroid of circle segment.

Kostas J. Spyrou, when he gave his keynote lecture, basically copied many concepts that were developed by Bar-Meir (such as the stability dome) and presented them as his ideas. These concepts had never appeared in the literature before. It is interesting to point out that Dr. Spyrou has been observed downloading Bar-Meir's book. Dr. Spyrou's behavior is not unique to him only. Dr. Kenneth Brezinsky went out of his way to declare that Bar-Meir's calculations of compressible gas potential were useless and baseless. However, Brian J. Cantwell from Stanford University recently decided to copy Bar-Meir's idea and to dedicate a whole section (2.9) to it in his book (and probably also in his classes). Except that Dr. Cantwell oversimplified the idea (he removed the dimensionless presentation), maybe because he did not fully understand it. The ship stability went major revision and basically revamped the field in particular the added mass (properties). The old governing equations yielding hundreds percent errors had to be modified due to discoveries of this author.

## Conflict of Interest

The author Genick Bar-Meir certify that he has NO affiliations with or involvement in any organization or entity or person with any financial interest (such as honoraria; educational grants; par-

ticipation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent–licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials or individuals discussed in this manuscript.

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