# Application report

## Vacu² Multi-Step Vacuum Process Revolutionizes Die Casting

**A joint project conducted by Pfeiffer Vacuum GmbH and Glimo N.V. has led to the development of Vacu² (Figure 1), a trailblazing, multi-step vacuum process for die casting. Asslar, Germany-based Pfeiffer Vacuum GmbH is highly regarded as one of the world's leading players in the field of vacuum applications, while Glimo N.V. has made a name for itself as a small consulting and development firm, up until now first and foremost in the casting industry.**

**Right from the very beginning, the developers set the bar high with respect to the project's innovation goals. The object was to utilize existing fundamental ideas to develop a revolutionary vacuum process for die casting that would eliminate the shortcomings of existing processes with respect to achievable vacuum, process reliability and process control. To do that, a combination scientific/hands-on approach was selected under which both computations and simulations were conducted as well as elaborate practical trials and measurements using a pilot plant. Figure 2 shows the layout of the current standard system. Taken into consideration, in particular, were the peculiarities and specific dynamic behavior of air, as a compressible medium, during the very quickly progressing processes. To further support the process concept, successful trials were conducted on existing die casting systems and molds in various foundries.**

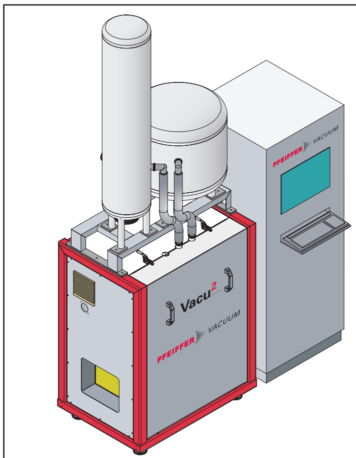

**Figure 2: Layout of the standard system**

### Conventional vacuum process

Vacuum has been employed for decades in connection with die casting. In the past, two processes, in particular, had become established practice:

> Under the "standard process" (Figure 3a), a recipient in which an underpressure has been established is connected with the mold cavity after the piston has traveled past the shot sleeve inlet

> Under other processes (Figure 3b), evacuation takes place even while the metal is being dosed.

Under both fundamental processes, the connection between the vacuum recipient and the mold cavity is primarily produced by means of an integral vent valve (vacuum valve) in the mold. Often elaborately manufactured, these valves are intended to prevent metal from entering the vacuum system, on the one hand, while nevertheless allowing as much air as possible to escape from the mold cavity. These kinds of contradictory requirements are the reason why some of these valves are relatively susceptible to malfunctioning or require intensive maintenance.

Two types of valves are widely available on the market:

> Mechanically closing valves (piston-type valves)

> Valves that retain the metal in a narrow gap when it solidifies ("washboard valves").

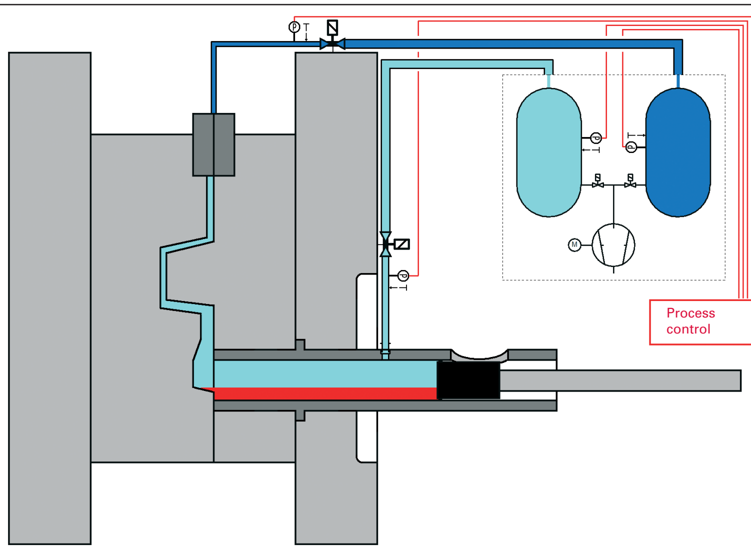


**Figure 1: Schematic diagram of one version of the multi-step vacuum process**

Vacuum die casting is indispensable for aluminum workpieces that have to be heat-treated or welded. However the vacuum process had not been able to achieve broad-based popularity for all other workpieces. The vast majority of castings continue to be fabricated without vacuum, and foundry operators do not always view vacuum processes in a positive light. The major reason for its sluggish acceptance can undoubtedly be found in several of the inherent weaknesses (such as the blockage effect or the need for improved process stability) that these processes have involved in the past.

**The blockage effect.** The primary task of a vacuum system on a die casting machine is to evacuate a given volume of air from the mold cavity and the shot sleeve within a short period of time (a view seconds). Conventional systems have to evacuate

this volume of air through the narrow gap formed by the gate, the geometric constrictions in the die casting mold, through the overflow connections, the vacuum channels in the mold and, last but not least, through the vent valve. Correspondingly poor conductivities can be expected. In addition, the physics of the blockage effect also muddies the waters. Under certain pressure conditions, the blockage effect occurs at the narrowest point in a line. In the most favorable case, i.e. if the vacuum system has been correctly designed, this would be the vent valve. As a result of extreme adiabatic expansion, the gases attain velocities equal to the speed of sound in the cross sectional area of this valve. As long as this condition persists, it is impossible to increase the volume flowing through it, neither through lower pressures in the recipient nor by increasing the size of the vacuum recipient.
Calculations and measurements show that the time available during die casting is insufficient in most cases for attaining anywhere near the desired vacuums. Absolute pressures of over 200 to as much as 500 mbar are customary. Experience has shown that lower pressures are encountered only relatively rarely. Many foundry operators therefore realistically tend to speak of "vacuum-supported casting."

In processes that dose the metal by means of vacuum, the time available for evacuation is increased by the dosing time, which means that, in principle, better vacuums can be achieved. However this technique involves other disadvantages:

> The dosing volume and the vacuum are not independent of one another
> The casting molds have to be elaborately sealed in order to achieve sufficient dosing accuracy
> The technology cannot be readily employed on every standard die casting system, as this would require a special furnace system that is connected with the shot sleeve via a riser pipe.

**Process stability.** Figure 4 shows a typical set of pressure curves of the type that are customarily encountered in connection with vacuum die casting processes. The upper curve represents the actual pressure in the mold cavity, and thus the primary result of the evacuation process. Unfortunately, it has not been possible to readily measure this value in the past, so it was therefore usually unknown to the foundry operator. The lower curve represents the values measured downstream from the vent valve. The actual pressure curve initially drops off steeply and then levels off at a given value.

Among other things, the steepness of the flank and the pressure level that is ultimately achieved are dependent upon multiple external parameters that govern the process (Figure 6, Column 1). The nature of the curve will vary significantly if there is:

> A change in the volume to be evacuated (casting size, shot sleeve volume, connections)
> A change in the leakage rate of the overall system (tightness of the mold, piston)
> A change in the conductivities of the overall system (as a result of contamination, clogging).

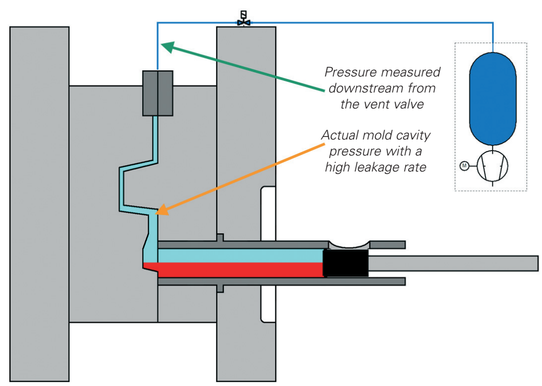


**Figure 3a: Standard vacuum process for die casting**

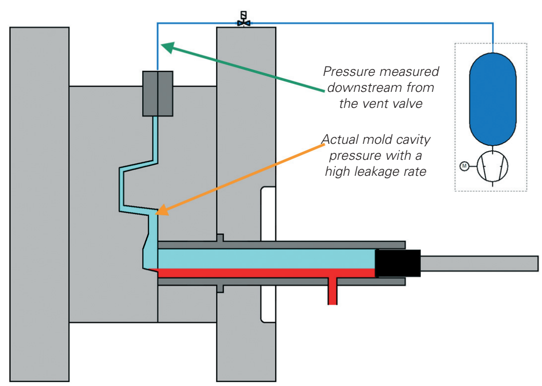


**Figure 3b: Vacuum process with metal being dosed during the evacuation process**

Figures 4 and 5 show the impact of the leakage rate on the ultimately achievable vacuum by way of example. Furthermore, in most cases the time available during the die casting process is insufficient for achieving the above-indicated vacuum. However even minor process variations during the steep portion of the curve will produce highly differing results. Fluctuations of over 100 % in the level of vacuum attained within a casting run are by no means uncommon.

**Process control.** Standard processes are monitored by measuring the pressure downstream from the vent valve. But how meaningful is this measurement with respect to the most important parameter, the pressure that is actually achieved in the mold or the maximum volume of air enclosed in it? This measurement is subject to various sources of error:

> The narrow cross section and the occurrence of the blockage effect do not allow any measurement that would be relevant to the pressure in the mold cavity to be conducted during the further course of the line. In actual practice, the pressure in the recipient has a greater influence on this measurement than the actual pressure in the mold
> This is a dynamic measurement. It is a known fact that the velocity of gases flowing through a line generates an additional underpressure. This falsifies the results of the measurement.
> Changes in conductivity (contamination, clogging) additionally lead to a considerable measurement error.

Figures 4 and 5 show that there are major differences in the actual pressure levels, although the measured (lower) pressure curves hardly differ from one another.
It is not possible to establish a reliable relationship between the main parameter of the process (= vacuum in the mold) and the measured value. The best way to illustrate this is through the well-known effect that the "best" vacuums that are measured occur precisely when the valve is contaminated or clogged, although in reality this is when the poorest vacuum levels are present.

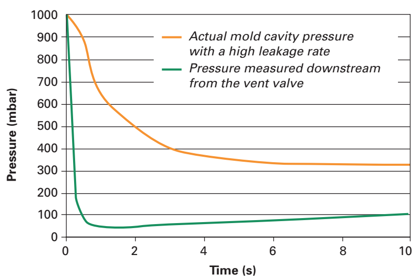


**Figure 4: Measured and actual pressures with a relatively leaky mold**

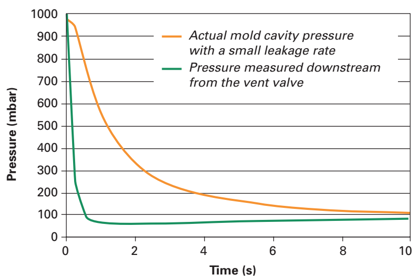


**Figure 5: Measured and actual pressures with a relatively tight mold**

Moreover, it would be illusionary to use this approach to monitor further major process variables, such as leakage rates or conductivity. It is not possible to use only one measured value in order to solve a system of equations containing multiple mathematical unknowns.

## The multi-step concept

The inadequacies of the legacy processes were the driving force behind the search for new approaches and the development of a process that would satisfy today's casting technology needs.

Figure 1 shows a schematic representation of the standard version of the new process. The solution shown has two vacuum steps and a direct connection to the shot sleeve. Depending upon the size of the machine, its charge and the required sealing effect of the piston, versions with a shot sleeve cover would also be possible.

Under the process, two mutually independent but coordinated vacuum steps are generated. In the first step, a vacuum recipient is connected with the mold cavity via the shot sleeve. After this recipient has been isolated from the shot sleeve again, the second vacuum step is initiated by connecting a further recipient with the mold cavity. This connection can be made via one of the conventional vent valves. Afterward, the recipients are returned precisely to their adjustable vacuum levels by means of a powerful combination of pumps that are specially matched to the vacuum die casting process in order to assure identical starting conditions for each shot.

**Recipient volumes.** Under the two-step process, the volumes and outlet pressures can be separately matched and set for each step of the process. If the system is correctly designed, the complete independence of the two vacuum circuits from one another eliminates the linkage between the parameters (Figure 6, Steps 1 and 2), so that each of the individual process steps is governed by only two primary variables. Eliminating the linkage between the two vacuum steps additionally increases the theoretically achievable vacuum exponentially. Since the second vacuum step can already begin with a pre-evacuated space, significantly lower pressures can be achieved with only a fraction of the comparable total recipient volume that would be required under a single-step process.

**Process stability and achievable vacuums.** The two-step process produces a totally different set of pressure curves than the single-step process (Figure 7).
The recipient volume, initial pressure and connection cross sections for the first step are designed in such a manner that – in contrast to the existing process – an equilibrium is produced between recipient and mold cavity, and an absolute pressure of some 50 mbar can be achieved in the mold cavity within as little as 0.5 to 1.0 second. With such fast processes, the leakage rate is hardly a factor. The pressure curves differ only marginally during the first-step portion (Figure 7). Nor is there any significant heat exchange, which means that adiabatic changes in the state of the gases can be assumed. It is naturally necessary to take into account the considerable temperature changes that result in connection with adiabatic expansion (Figure 6, Step 1).

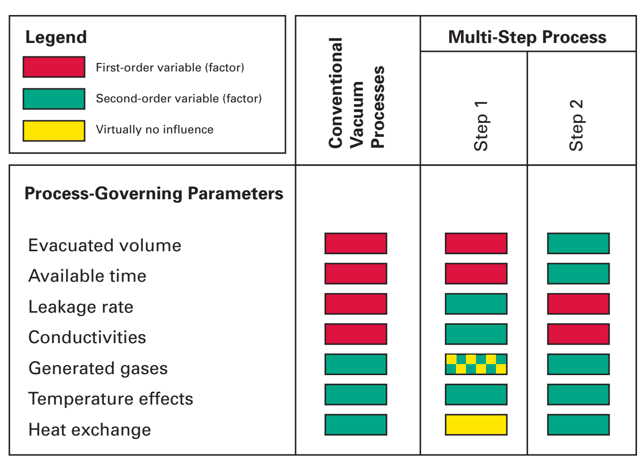


**Figure 6: Significance of external parameters under the various vacuum processes**

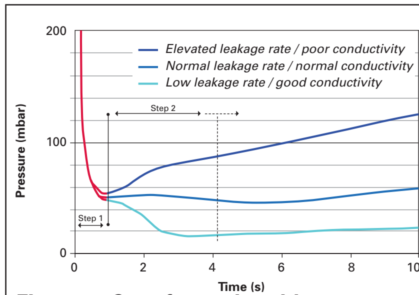


**Figure 7: Set of actual mold pressure curves with the two-step process**

The starting value at the beginning of the second step is far lower than in classical processes. Since nearly the entire volume of air was already removed during the first step, volume and available time play only a secondary role in influencing the second step. In fact, the stability criteria are reversed. The pressure levels actually change all the less the greater the workpiece volume of the casting and the shorter the remaining time (Figure 6, Step 2). The changes in the pressure level during the second step of evacuation are slower than in the first step. The pressure can either rise or fall, depending upon the leakage rate and conductivity of the overall system. Ultimate pressures of 20 mbar have already been achieved (Figure 7). However the stable pressure curve is an even more important factor than the absolute volume. Variations in process conditions result in only minor changes in the vacuum achieved. An impact analysis was able to demonstrate that changes in one step are attenuated by the other step. As a result of these altered interdependencies, vacuum casting is now fundamentally possible in connection with molds that have higher leakage rates, with slide-equipped molds, less elaborately sealed molds or molds with very large volumes.

**Process control.** Comprehensive process control is an absolute prerequisite for modern production processes. Rising demands with respect to workpiece quality, process documentation and cost optimization now mean that modern casting systems are equipped with sophisticated process monitoring systems that allow most process parameters to be monitored and set. So it is necessary for vacuum systems, as an element of the die casting cells, to keep pace with this development and be integrated into the control systems of die-casting machines. In addition to the main parameter of "vacuum," it is also necessary for changes in other process-governing "interference variables" (leakage, conductivity) to be monitored and documented.
This is why process control (Figure 1) is justly considered to be the actual heart of this new process. In addition to a stored program control (SPC) system that regulates the actual process operations, the system is also equipped with PC-based process monitoring. Only with a powerful computer was it possible to integrate the sophisticated, yet necessary algorithms into the process control system in order to be able to determine both the vacuum achieved as well as variances in leakage and flow rates for every shot on a near-realtime basis. Of course, valid, sufficient and precise measurement data are an initial prerequisite for any kind of meaningful computations.

The following approach is selected in order to eliminate the fundamental mathematical unknowns in the above-described system of equations:
> Measurements by means of highly accurate absolute pressure probes (resolution < 0.5 mbar) are conducted in four locations:
  – The smaller recipients make the pressure measurements meaningful here
  – Both static and dynamic measurements can be conducted in the lines at different times
> The calculations take into consideration the laws governing compressible media
> Mathematically, the individualized parameters are viewed independently of one another as first-order factors

Before the actual casting operation can begin, various tests have to be conducted to determine the characteristic values of the system, consisting of the die-casting machine, the mold and the vacuum system, and compared with previously recorded data. This assures that reproducible starting conditions will prevail and that the parameters will be within the required limits.
During the casting operation, the process is monitored on the basis of five parameters. Two of these parameters are determined directly, while three are derived on the basis of measurements. The actual ultimate pressure in the mold cavity, as well as changes in leakage rate and conductivity, are displayed. The monitoring parameters are associated with each shot and documented. They can be assigned intervention and malfunction limits. To simplify operation, the process parameters at the beginning of the casting process are suggested when the process control system is set up (recipes and recipe administration).

## Tests and results

A pilot plant was used to conduct tests in various foundries on die-casting machines ranging in size from 7,000 to 35,000 kN.
To determine the potential applications for this process, tests were conducted on both sealed and unsealed molds, as well as on molds with multiple slides. All application combinations produced excellent results with respect to the vacuum achieved and the quality of the workpieces. It is still desirable to seal the mold to a certain degree, which benefits both workpiece quality and process stability. Depending upon the application in question, absolute pressures of between 20 and 100 mbar were achieved in the mold. Workpiece quality was assessed on the basis of:
> Mechanical properties
> X-Ray
> Glow tests
> Welding tests
Significant differences in the quality of the castings were able to be evidenced at an absolute pressure of 40 to 50 mbar.

Accompanying studies were also conducted on the characteristics of vent valves and pistons, as well as on the influences of mold design.
The simulated values displayed very good correlation with the values measured in the real world and confirmed the forecasts relating to the influences of volumes, initial pressures, conductivities, leakage rates and temperature effects.

## Outlook: Cost savings potential and fields of application

This new process offers die-casting operators a wealth of cost-saving potential:
> Better vacuum translates into better workpiece quality
> Reliable process monitoring reduces the rejection rate, as process variances can be identified early on and countermeasures initiated
> Greater process transparency speeds up optimization of the entire die-casting process, as it eliminates the need for trial & error procedures
> Because the process is less susceptible to leakage and conductivity, the time and expense required for mold-building can be reduced and precisely tailored to the requirements in question. Molds only have to be tight enough for the process and the workpiece in question. The altered interdependencies between the second vacuum step and the process variables pave the way for re-thinking the previous dimensioning and design of vent valves and channels and for developing alternative designs.

The process also offers further opportunities to benefit from vacuum, such as in connection with:
> Slide-equipped molds or large workpiece volumes. These now no longer pose any fundamental obstacles with respect to generating high-quality vacuum.
> A broader class of demanding workpieces, where the new technology is especially worthwhile.

Ultimately, the multi-step vacuum process has what it takes to serve as a full-fledged element of the modern die-casting process, because it satisfies today's requirements with respect to process reliability.
There is every indication that in the future, vacuum will be able to be employed profitably, reproducibly and reliably in foundries on a wide scale basis.



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