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Reduction of Oxide Inclusions in Aluminum Cylinder Heads through Virtual Design of Experiments

Executive Summary

Oxide inclusions, which are created during the pouring process of aluminum alloys, are the main cause of leaks in castings. This contribution shows how the integration of virtual design of experiments (vDOEs) into the casting process simulation tool MAGMA^5 provided the basis for the evaluation and subsequent optimization of process parameters in the melt transport and pouring process, which are responsible for the creation and distribution of oxide inclusions. At the same time, quality criteria describing the creation of oxides during the casting process of cylinder heads was evaluated quantitatively. The utilization of vDOEs creates variations of the gating system and process parameters autonomously. It will be shown that vDOEs are leading to optimized gating designs and process parameters resulting in a significant reduction of oxides in castings. The experiments supported by simulation were accompanied and validated by high-speed video technology and the PREFIL-measurement technology.

Introduction

Oxide inclusions, which are created during the pouring process of aluminum alloys, are deemed the main cause of leaks in thin-walled aluminum castings like cylinder heads. The oxide skin, which is created in fractions of seconds on the surface of aluminum melts, isn’t dissolved or re-melted due to its high melting temperature and remains in its solid state inside the casting. Any pouring process leads to turbulence at the melt surface. This leads to a break-up of the oxide skin, which then is entrained into the melt. Oxide skins lead to a material separation within the microstructure, which, depending on their size, can cause a reduction in local mechanical properties, or, especially in thin casting walls, they can cause leaks.

The damaging effects of oxides on the quality of castings can in the real world only be evaluated through experiments, i.e. leak tests on castings, after castings have been produced. The location of oxides, their distribution and the leaks they cause, are difficult to predict and are almost impossible to quantify. Literature [1, 2] describes potential causes and mechanisms that create oxides during the melting and pouring processes of aluminum alloys. However, the qualitative and quantitative evaluation of each root cause for the creation of oxides in each process step of the production process of cylinder heads has so far not been comprehensively evaluated.

An efficient evaluation of the many different impact factors of the mold filling process on the quality of a cylinder head is only feasible through the utilization of casting process simulation. The simulation of flow phenomena and the mold filling process is an accepted standard procedure in the industry. Different simulation methods have been proposed in the last few years to describe the creation and transport of oxides during the mold filling process [3-7], however, many of these models are only available as 2-dimensional models. Due to their complexity and the computing demands, they are not applicable to the specific conditions of aluminum alloys and are almost useless in foundries due to their extremely long calculation times.

The current version of the simulation software MAGMA[5] offers an easy to use, meaningful, and quantifying option to evaluate the potential of oxide creation during the mold filling process of complex castings. The complete integration of virtual design of experiments (vDOEs) through autonomous optimization technology leads to the development of optimized gating systems and process parameters in a very short time frame, which can even be utilized early in the design process of a casting.

Experimental Melt Quality Evaluation

The melt quality was experimentally evaluated for different process steps. The PREFIL system used for this evaluation is based on the filtration of a liquid aluminum sample, which is passed through a ceramic filter under controlled conditions. The qualitative evaluation is performed on samples, which are extracted near the filter.

The number, thickness, and length of oxide particles were evaluated using metallographic methods (figure 1).

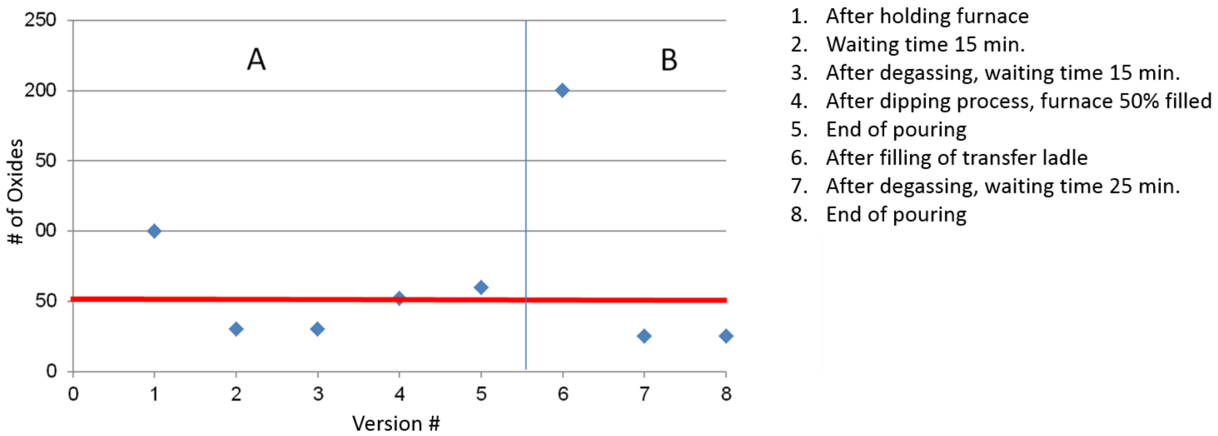


Fig. 1: Measured number of oxides in the melt (PREFIL-method) for different process steps in two cylinder head production lines A and B. The red line marks the limit of 50 oxide skins per kg of melt.

Samples #1 through #5 have been taken from a cylinder head production line (A) with its melt being composed of 84% of virgin alloy and 16% of re-melt. Samples #6 through #8 are from a second production line (B) composed of 45% virgin material and 55% re-melt.

The number of oxide skins found in samples #1 and #6 significantly exceeds the established limit of 50 oxide skins per kg of melt and is, therefore, not acceptable. Melt transfer processes between the furnaces cause these extremely high values, especially when the transport ladle is emptied. The amount of oxide skins inside the furnace (sample #5) is still a little above the critical limit at the end of the pouring process. The oxide skin content of the melt can be reduced after the transfer processes though the establishment of sufficient holding times before or after the degassing treatment. A significant reduction in oxide skins is shown with the implementation of such (samples #2, #3, and #7). The results confirm that it is desirable to utilize a turbulence reducing transfer method, especially when emptying a ladle.

Experimental Evaluation of Flow Phenomena

High-speed video technology, providing up to 1000 images per second, was used for the qualitative evaluation of flow phenomena during the different process steps (figure 2).

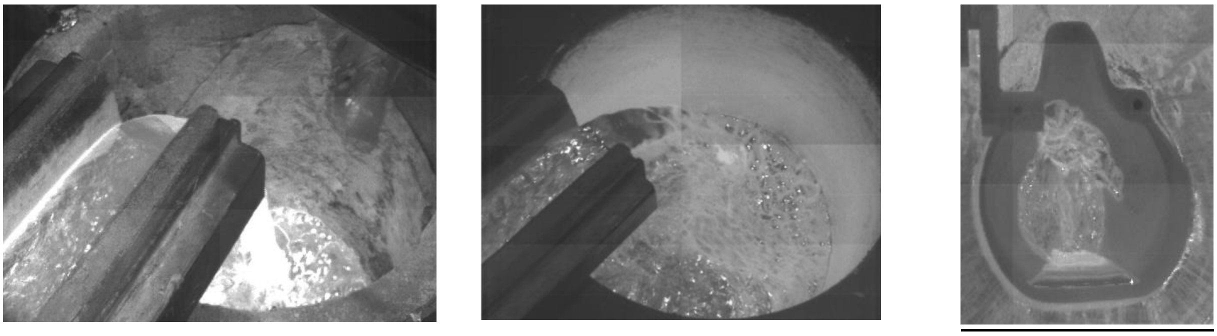


Fig. 2: Evaluation of transfer processes with high-speed videos. Filling of transfer ladle (left), filling of holding furnace (center), filling of pouring ladle (right).

Transporting the melt from the melting furnace to the holding furnace happens via an extended pouring spout when both are in close proximity, or a transfer ladle when a bigger distance needs to be covered. After the melt treatments, the melt will be transferred into the mold via a pouring ladle. With each transfer turbulences are created on the melt surface. This is a main cause for the creation of new oxides within the melt.

The videos show the mixing of the oxide foam swimming on the melt surface with the falling melt stream is clearly visible. The observations from the transfer processes match the results of the PREFIL-measurements. All samples derived from the spout or the transfer ladle after filling of the holding furnace show values in excess of the critical limit (see also figure 1). After the melt treatment inside the pouring furnace (degassing and holding), the number of oxide skins found in the melt is reduced.

The filling of a cylinder head creates a complex flow process. Turbulences caused by the free falling melt in the gating system and when exiting from the gating system into the mold cavity cannot be completely eliminated, but can be reduced. The melt then flows through the different cores. Controlling the flow and reducing turbulence in the complex cavities of a cylinder head with wall-thicknesses of 4mm requires a lot of experience and a fundamental understanding of flow phenomena.

During the design of runners and the location of gates between the runner and the casting, it is essential to consider melt velocities and to establish laminar flow conditions to avoid undesired flow phenomena when filling the cores. A non-optimal flow direction during the mold filling might lead to a local premature solidification on a core’s surface. This leads to an oxide skin, which will be entrapped during the subsequent filling process and will remain in the casting (figure 3). The intricate inside contour of the mold and the thin walls of the cylinder head increase the risk of oxide inclusion defects and resulting leaks, as trial runs with gravity cast cylinder heads confirmed (Figure 4).

Fig. 3: Change in flow direction during the mold filling process of a cylinder head. The cover core was modified to allow high-speed videos of the melt flowing from the runner through the gates to be taken.

(a) Cut through leaking cylinder head

(b) Fracture analysis through leaker

(c) Microstructure analysis

Fig. 4: Root-cause analysis on a leaking cylinder head. Leak tests under water indicate two leakers through rising bubbles (a). The fracture analysis shows an oxide skin spanning the entire thin wall (b). The microstructure analysis confirms the cause for the leaker (c).

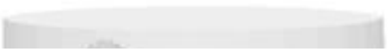
Quantitative Analysis of Oxide Creation and Optimization Opportunities Through the Utilization of Casting Process Simulation

Casting process simulation provides the quantitative impact evaluation of process parameters on the creation of air entrapment and oxides for the entire casting process – from melting all the way through to pouring the casting.

Several quality criteria are used to evaluate the total amount of entrapped air and resulting creation of oxides:

1. The amount of entrained air during the mold filling process
2. The accumulated free melt surface over the entire filling process
3. The amount of time the melt is exposed to air throughout the filling process (criteria 2 and 3 are indicators for the tendency to create oxides)
4. A criteria function depicting the locations where air is entrained during the mold filling process
5. Virtual particles in the melt (tracers), which are also reviewed to evaluate the flow during the mold filling process. These particles can also experience buoyancy and float or sink depending on their assigned mass.

Figure 5 shows examples of such quality criteria: the simulated entrainment of oxides through tracers, the calculated amount of entrapped air during the filling of the pouring ladle, and the velocity distribution inside the melt during the filling of the cylinder head. It is essential for all calculated quality criteria that they provide quantitative results. With that, the impact of changes in the gating system or process parameters (design parameters) can be evaluated and autonomously optimized through objectives defined in the casting process optimization program.



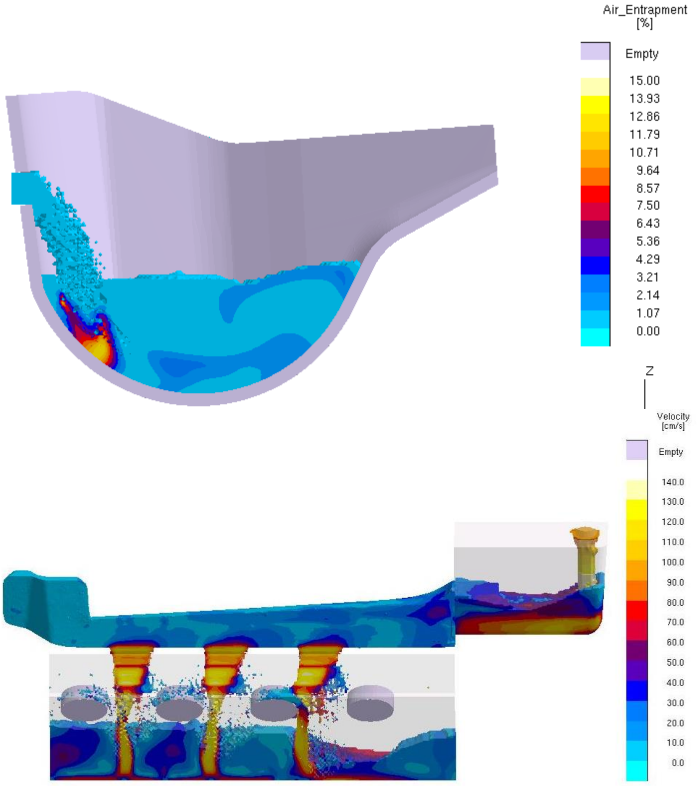
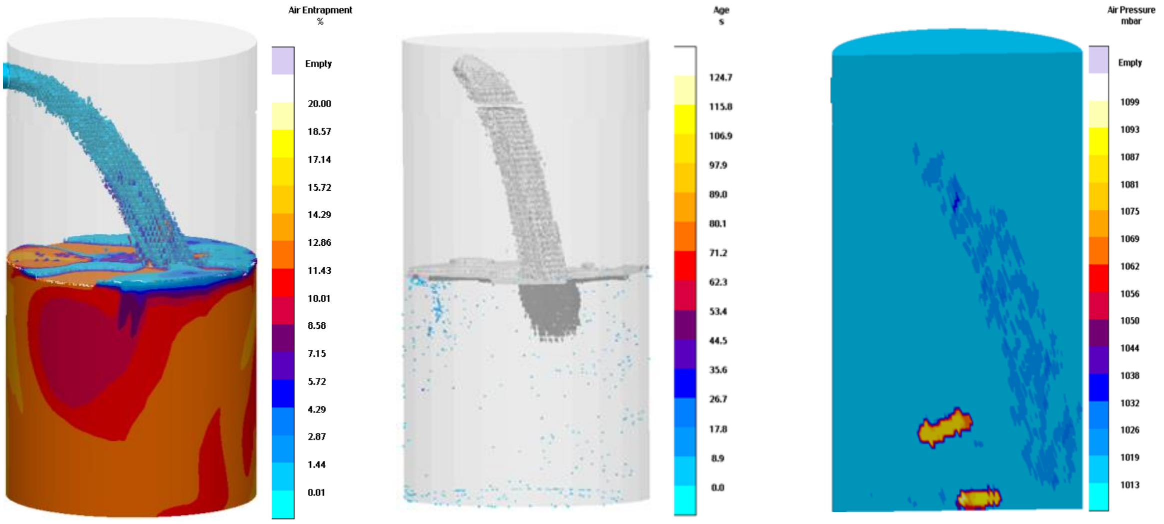


Fig. 5: Examples of quality criteria of a casting process simulation tool used for the evaluation of oxide creation tendency, oxide entrainment (left), entrapped air (upper right) and flow velocities (lower right).

The first casting process simulation evaluated the transfer process from a melting furnace to a holding furnace. The dimensions of the holding furnace are 60cm for the diameter and 150cm for its height. The total fill time is 60 s.



a) Air inclusions

b) Free melt surface and oxide particles

c) Location of air entrainment

Fig. 6: Transfer of melt from melting to holding furnace. Criteria were calculated after 30 s filling time. Simulated air inclusion distribution during filling (a), display of free melt surface including the entrainment of oxide particles (b). Amount of entrapped air shown in center cut through holding furnace (c).

The simulation results show how air is entrained in the melt when the aluminum stream dives into the melt inside the holding furnace (figure 6 (a)). This process, as well as the movement of the entrained air inside the melt that is affected by its buoyancy and convectional forces, are causes for the entrainment of oxides into the melt (figure 6 (c)).

The amount of oxide inclusions inside the melt at the end of the holding furnace filling derived from the simulation results confirms that a large pouring height leads to the entrainment of oxides, which are created on the melt surface through the metal stream. Therefore, it is essential to establish transfer processes that minimize the entrainment of air and the creation of oxides. It is also advisable to place the casting’s pouring location as close as possible to the holding furnace, so the use of transfer ladles can be eliminated.

Simulation and Optimization of the Pouring Ladle Filling Process

The video analysis of the filling process of a pouring ladle detected high surface turbulences. Thereby, the pouring ladle is dipped horizontally 2cm below the melt surface and filled via a thin rectangular opening. The goal of the virtual DOE was to establish process conditions that lead to a smooth filling of the ladle. At the beginning of the dipping process, the ladle is tilted backward at a specific angle, prohibiting the melt from falling freely out of the opening and allows it to flow smoothly the contour of the ladle. Later in the process, the pouring ladle is tilted back to the original horizontal position.

The virtual DOE is supposed to find the best initial tilting angle and the optimal point in time and speed of rotating it back to the horizontal position. The start angle and the total filling time were defined as process variables (start angle can vary between 0° and 50° in 10° steps, the total filling time can vary between 5.1 s and 6.9 s. in steps of 0,9 s (figure 7).

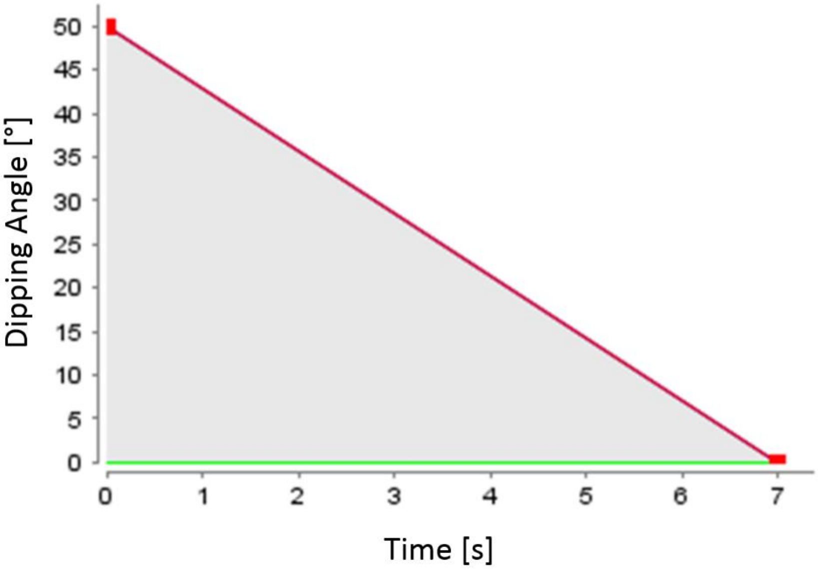


Fig. 7: Definition of process variables “start angle” and “total fill time”

This leads to six (6) different start angles and three (3) available filling times resulting in 18 process versions. The automatic evaluation of all 18 calculated versions is based on the previously defined goals. The optimization program used the free melt surface as quality criteria to evaluate the smoothness of the filling process. The goal, therefore, was to minimize the accumulated free surface during the filling process of the pouring ladle.

The correlation between process versions and desired goals can be evaluated in different ways by the software. One meaningful approach is the utilization of scatter charts for all results. These display correlations between changes in process parameters and their impact on different quality criteria for all calculated versions. In addition, it is possible to display the significance of each process variable on each quality criteria.

In figures 8 and 9, each point in the diagraph represents one calculated version. The results show that the start angle of the pouring ladle has a large impact on the quality criteria “free surface”. The larger the tilt angle at the beginning of the filling process, the lower the value is of this criteria, meaning the less turbulent is the filling.

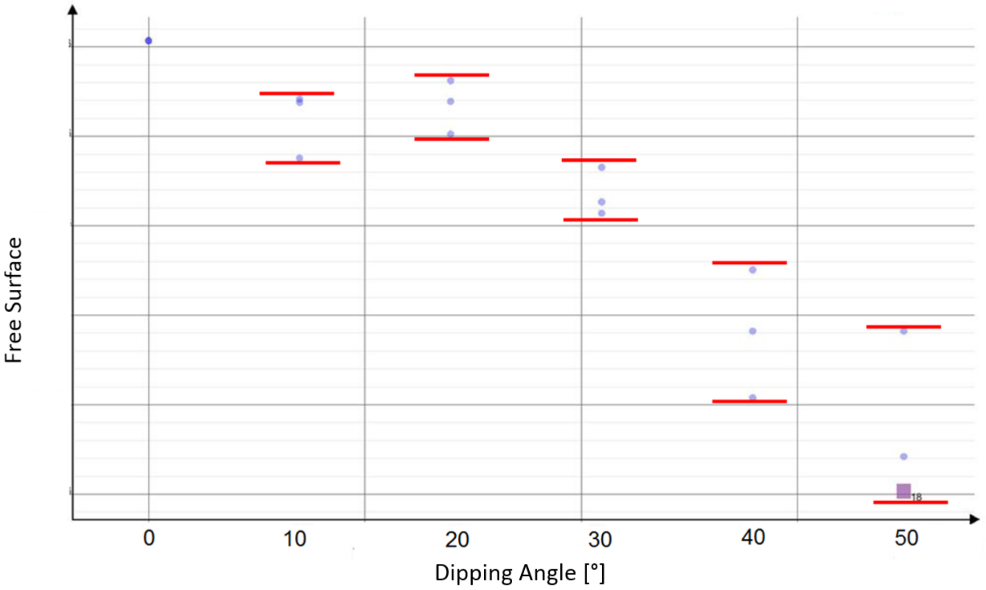


Fig. 8: Quality criteria ”free surface“ as function of the start angle of the pouring ladle.

However, the results also reflect that the total filling time has a negligible impact on the accumulated free melt surface (figure 9). The best combination is a start tilt angle of 50 degrees and a filling time of 6.9 s (purple square in figure 8 and 9 lower right).

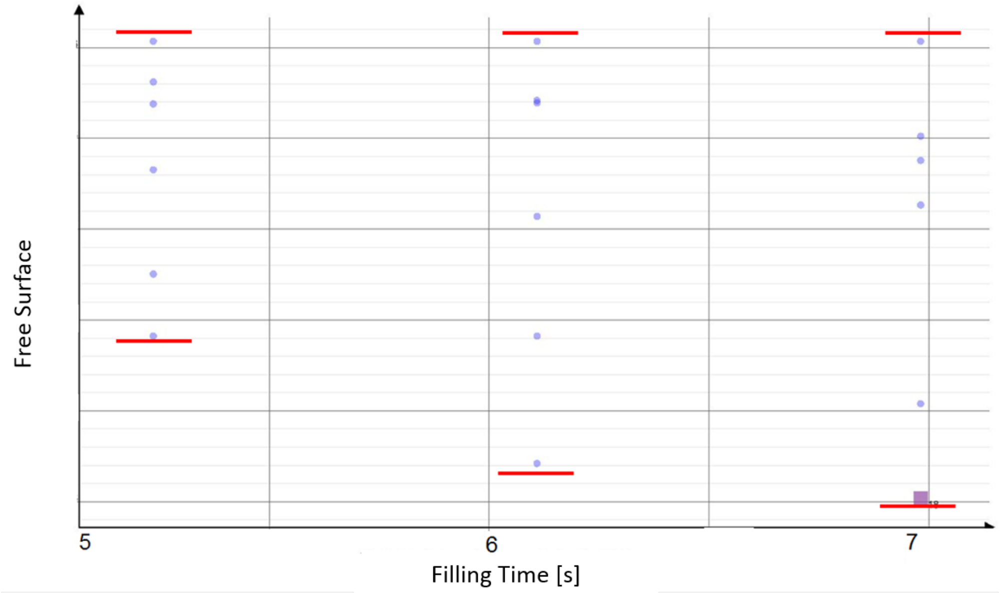


Fig. 9: Quality criteria ”free surface“ as function of the filling time of the pouring ladle.

Figure10 shows the development of the “free surface“ over the entire filling process for the initial and the optimized versions. The best version reaches the maximum value for the free melt surface after about 1 s. At that point in time, the melt has filled the entire diameter of the pouring ladle. After that, the free surface remains approximately the same, which is an indicator for a smooth filling. In the initial version, the maximum value for the free surface was reached after 1.5 s, but was three times bigger than the one established in the optimized version.

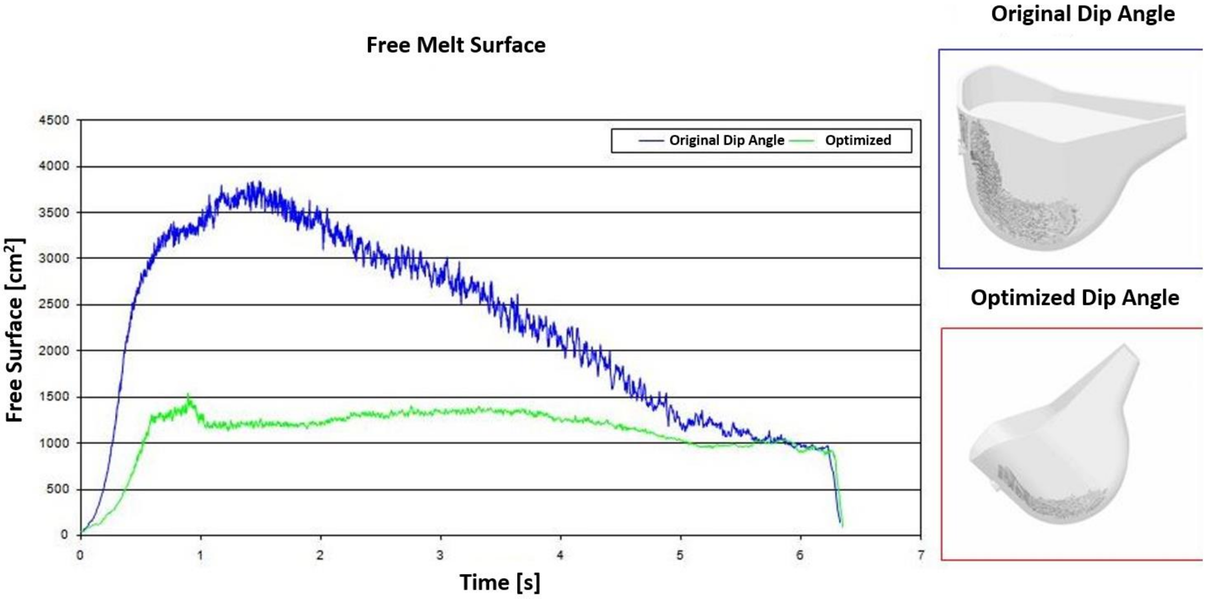


Fig. 10: Calculated development of “free melt surface” over the entire filling process.

The significantly higher values for the free surface are caused by turbulence inside the melt. The melt reaches velocities above 70cm/s at the bottom of the pouring ladle after exiting the opening. The melt stream continuously entrains air and oxides (figure 11). The optimized version shows no such air entrainment.

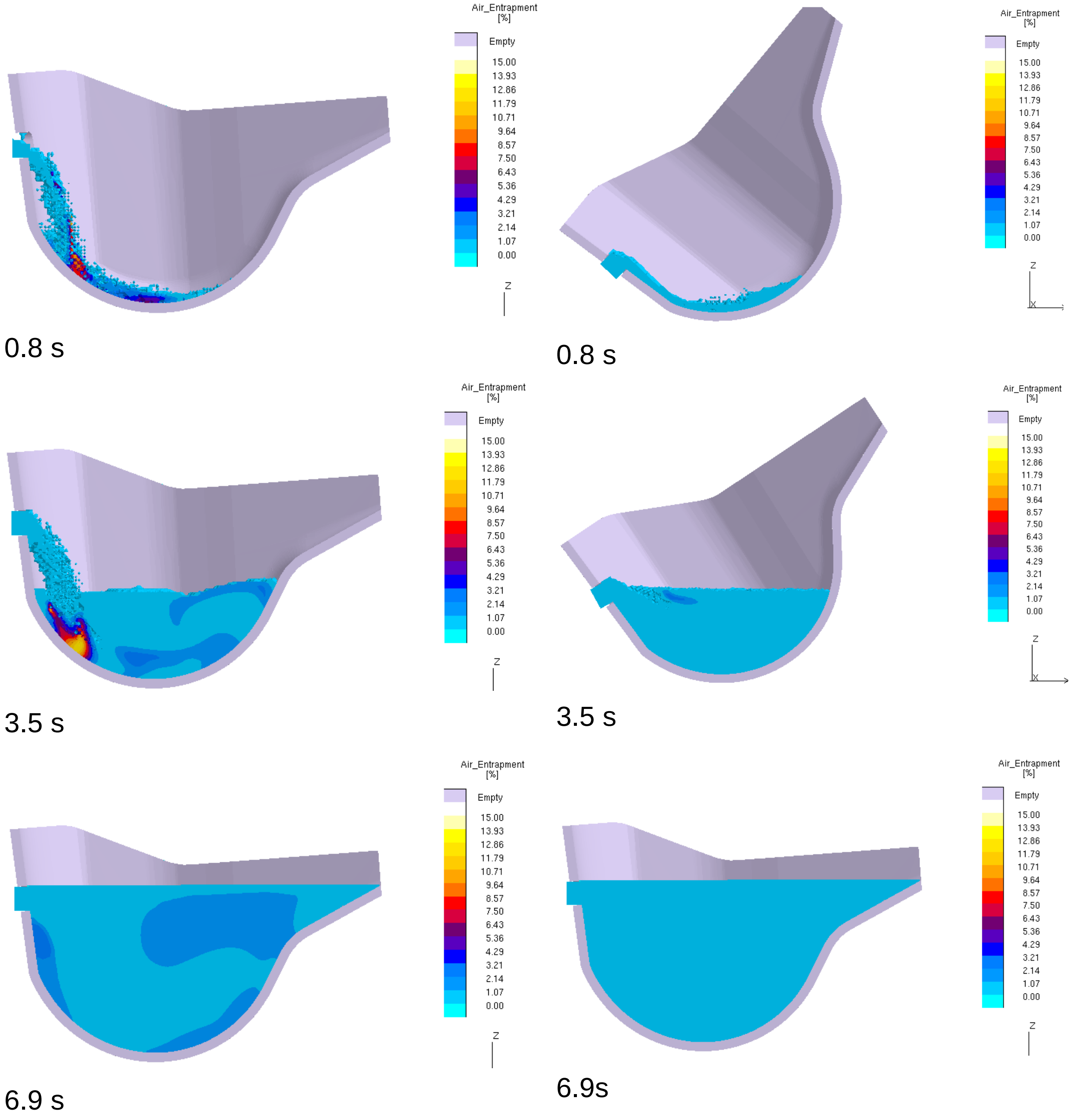


Fig. 11: Air entrapment during filling process of pouring ladle comparing the initial process (left) and optimized version (right) (cut through center of pouring ladle).

The criteria “air contact”, refers to the time each melt particle is in contact with air, is an important indicator of the amount of oxides created. In the initial version, almost the entire melt volume is exposed to air for a longer period of time (figure 12) compared to the optimized version, where a stable melt surface is established much faster.

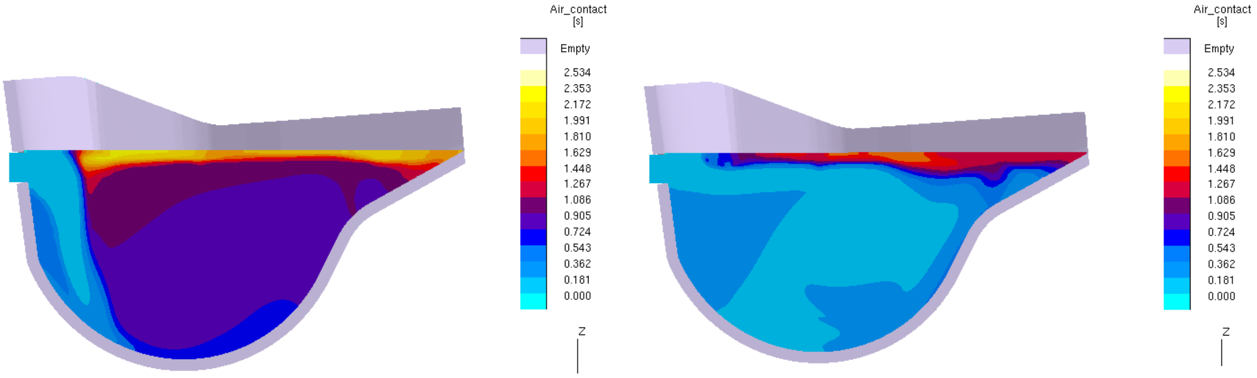


Fig. 12: Comparison of air exposure between stationary filling (left) and optimized, tilted filling (right) (cut through center of pouring ladle).

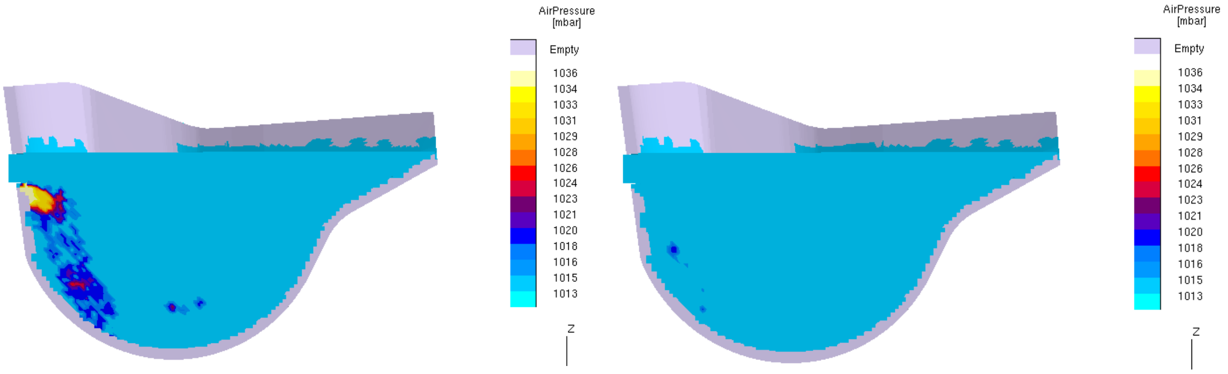


Fig. 13: Comparison of location where air is entrapped during stationary filling (left) and optimized, tilted filling (right) (cut through center of pouring ladle). The initial version entrained air mostly during the initial free fall of the melt out of its opening into the pouring ladle.

The simulation results show that the entrapped air bubbles are moving towards the surface of the melt due to their buoyancy and melt turbulence. They are leaving a trail of oxides along the way. As the melt enters the gating system and the mold cavity straight from the pouring ladle, all oxides existing at that time will enter the casting with detrimental impact on its quality.

Gating system optimization for cylinder heads

Leaks caused by oxide inclusions were the main source of defects for the evaluated cylinder head. The analysis of the mold filling process through high-speed videos and the simulation of the mold filling process of the original geometry demonstrated the potential for its optimization. Melt quality and how the mold is filled both have a direct impact on the amount and distribution of oxide inclusions in the casting. The original gating system created the following main contributors to the creation of oxides:

- Immense melt turbulence in the pouring basin
- High melt velocity in the main runner
- Less than optimal flow direction of the melt when entering the mold cavity through the gates

A virtual DOE was used to evaluate and quantify the impact of several geometric modifications of the gating system and process parameters on the creation of oxides, as well as the entrainment of already existing oxides into the casting and their distribution.

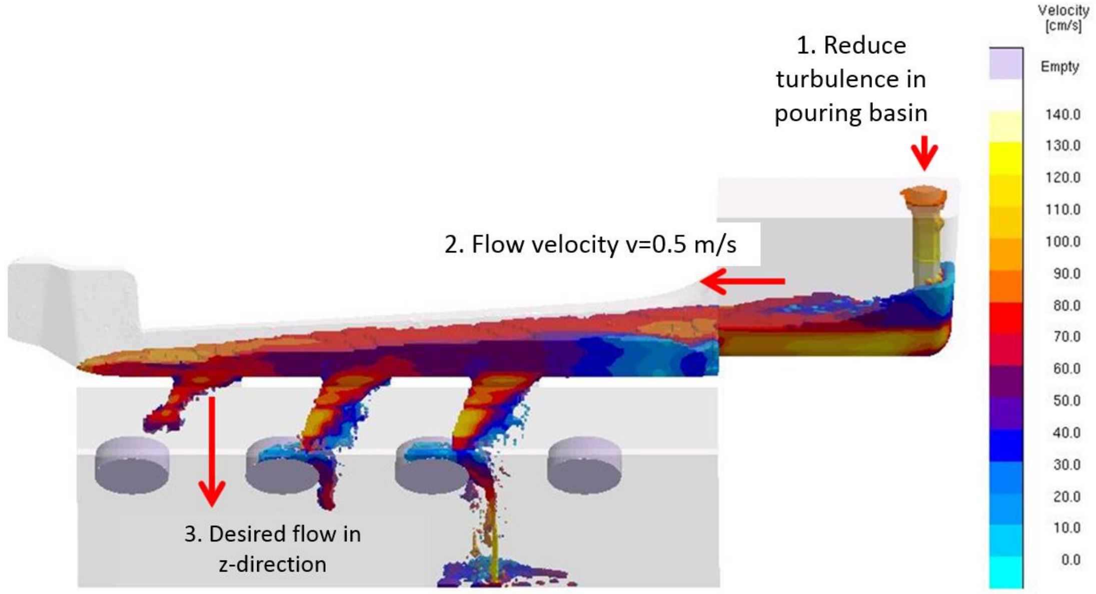


Fig. 14: Schematic display of optimization goals of the virtual DOE

The first goal for the vDOE was to to find an optimized layout of the gating system that will minimize the turbulence (and oxide creation) in the pouring basin.

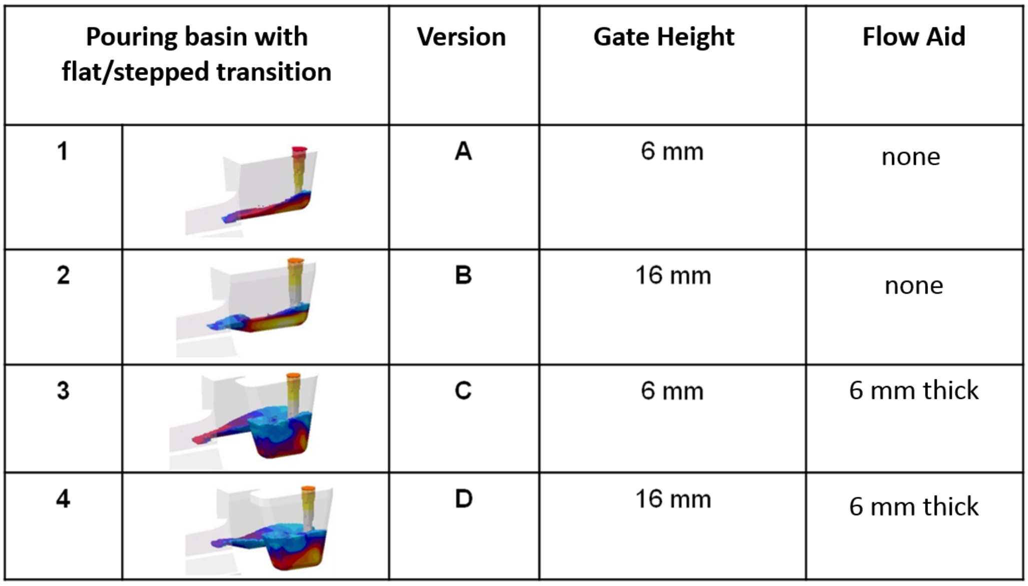
The pouring height and orientation of the melt stream was varied (hitting the rear pouring basin wall versus the pouring basin’s bottom) to reduce the originally observed back wave of the melt collapsing on itself when hitting the pouring basin walls (figure 14 (1.)).

The second goal was to reduce the velocity of the melt when leaving the pouring basin and entering the runner. Besides using runners which were directly connected to the pouring basin, a deviation basin was evaluated. Several alternatives for the transition between the pouring basin into the runner (rising or stepped versus flat) were expected to support the desired velocity reduction (figure 14 (2.)).

The third goal was to realize a constant vertical flow from the gates towards the water jacket cavity inside the cylinder head. This was supposed to reduce or even eliminate premature solidification of the melt on the channel cores. Elongated gates and additional flow aids below them were the variables of this optimization aspect (figure 14 (3)).

The optimization runs in MAGMA[5] used a parameterized geometry of the original gating system. The complex cylinder head geometry was substituted for efficiency reasons by a simplified geometry. The wall thicknesses and angle of the wall below the gates, as well as the position of the channel cores, exactly matched the configuration of the real cylinder head.

Adding up the following geometric variations: central or back-wall filling of the pouring basin, flat or rising transition from pouring basin to runner, short tor long gates, and present or non-present filling aids lead to 16 to be calculated versions (figure 15).



Pouring basin with flat/stepped transition		Version	Gate Height	Flow Aid
1		A	6 mm	none
2		B	16 mm	none
3		C	6 mm	6 mm thick
4		D	16 mm	6 mm thick

Fig. 15: Trial plan and nomenclature for the 16 evaluated variations

The following functions for the evaluation of all simulation results were defined:

1. Minimize the maximum melt velocity in control point C1 in the transition between the pouring basin and the runner
2. Minimize the melt volume through gates A1, A2, and A3 with undesired flow direction (deviation from z-direction) (figure 16)
3. Reduce the accumulated “free surface“ of the melt during the mold filling process

The virtual DOE was run automatically in MAGMA[5], including the generation of the geometry variations, their enmeshment, the calculation and evaluation of quality criteria and functions for the evaluation of all simulations.

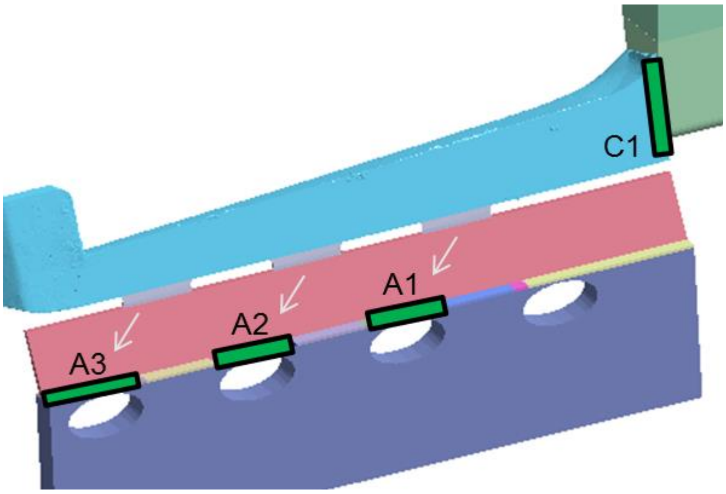


Fig. 16: Definition of evaluation areas A1, A2, A3 for the evaluation of the deviation of the melt flow from the desired z-direction and the location of control point C1 for the melt velocity evaluation

Optimization Evaluation

Velocity Reduction in the Runner

The melt front velocity of aluminum alloys is not to exceed 50 cm/s to avoid instabilities and surface turbulence at the melt front [1], which lead to an increase of the free surface area of the melt, which results in oxides inclusions. The velocity reduction can also support the creation of the desired vertical melt flow direction exiting the gates.

The evaluation shows a clear dependency of the melt velocity at the control point on the evaluated design and process variables (figure 17). Versions 4A through 4D are the best, as they are showing velocity values very close to the goal of being below 50 cm/s, which is a reduction of 50% compared to the starting configuration (A1 with 105.7 cm/s).

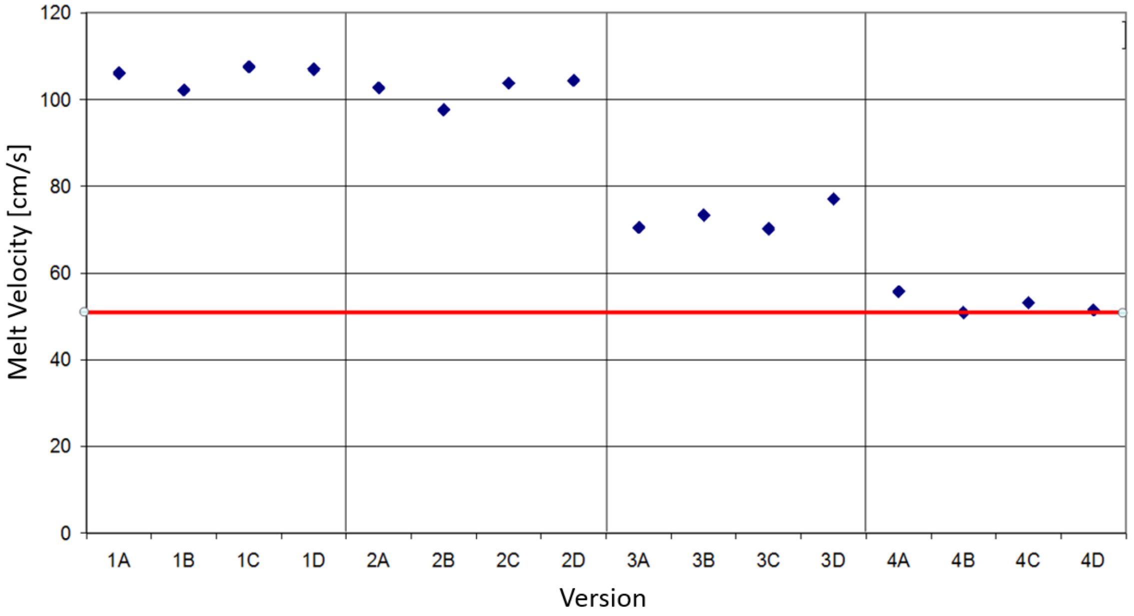


Fig. 17: Average melt velocity at transition between pouring basin to runner (control point C1) for all evaluated designs. The red line depicts the desired critical value of 50 cm/s melt velocity.

Controlling the melt flow direction out of the gates

The second goal was to establish a vertical flow of the melt out of the gates into the casting without hitting any of the cores. The melt not flowing in the desired z-direction is shown for all versions in figure 18. It is clearly shown that the melt flow direction in gate A1 deviates the most of all versions from the desired z-direction. This is caused by the pressures and kinetic energy values, which decrease from gate to gate. The evaluation also shows that for all “D-versions”, meaning independent from the pouring basin geometry and its connection to the runner, show the least melt volume deviating from the desired flow direction. Version 4D is the best, as only 52 cm^3 melt from all three gates is deviating from the desired flow direction. A closer evaluation of the simulation results of that version also shows that the melt is only barely touching the channel core sides (figure 19).

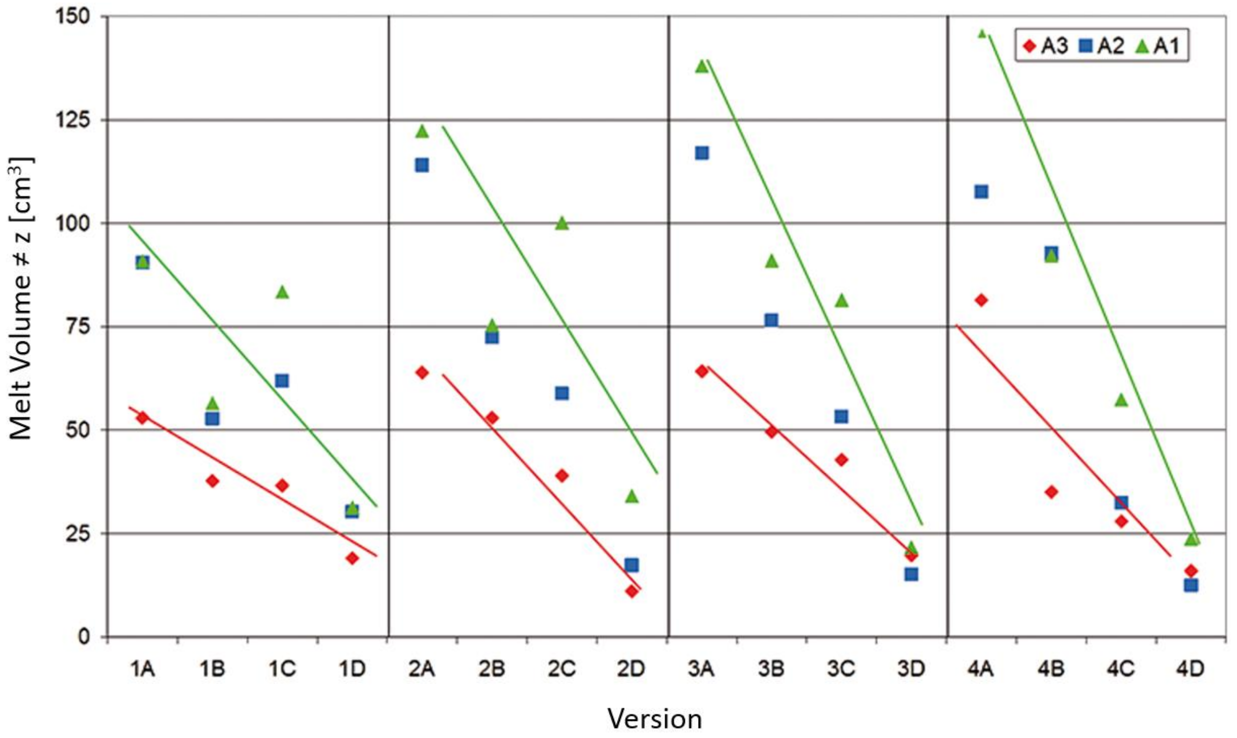
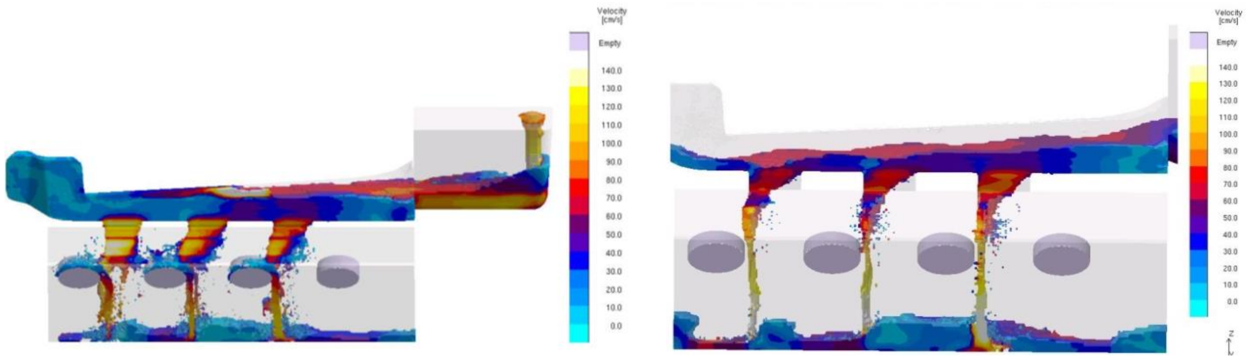


Fig. 18: Melt volume [cm^3] deviating from the vertical (desired) flow direction in gates A1 through A3 for all 16 versions



Version 1A; 2,67 s

Version 4D; 3,84 s

Fig. 19: Comparison of melt velocities and direction for versions 1A and 4D at the same point in time.

Reduction of Free Melt Surface

The criteria “free surface“ in MAGMA[5] measures the melt in contact with air during the mold filling process. This criteria can be used at specific times during the mold filling process (figure 20) or show accumulated values over the entire filling process (figure 21).The geometry changes in the gating system lead to differences in volume and weight between the versions. The melt volume in version 4D is 4.48 liters and is, in comparison to versions 1A with 2.82 liters, about 62% bigger. Despite that fact, the accumulated free surface shrinks by about 5% from 120,678 mm^2 of version 1A to 114,944 mm^2 in version 4D. The oxide creation risk is thereby significantly reduced (figure 22).

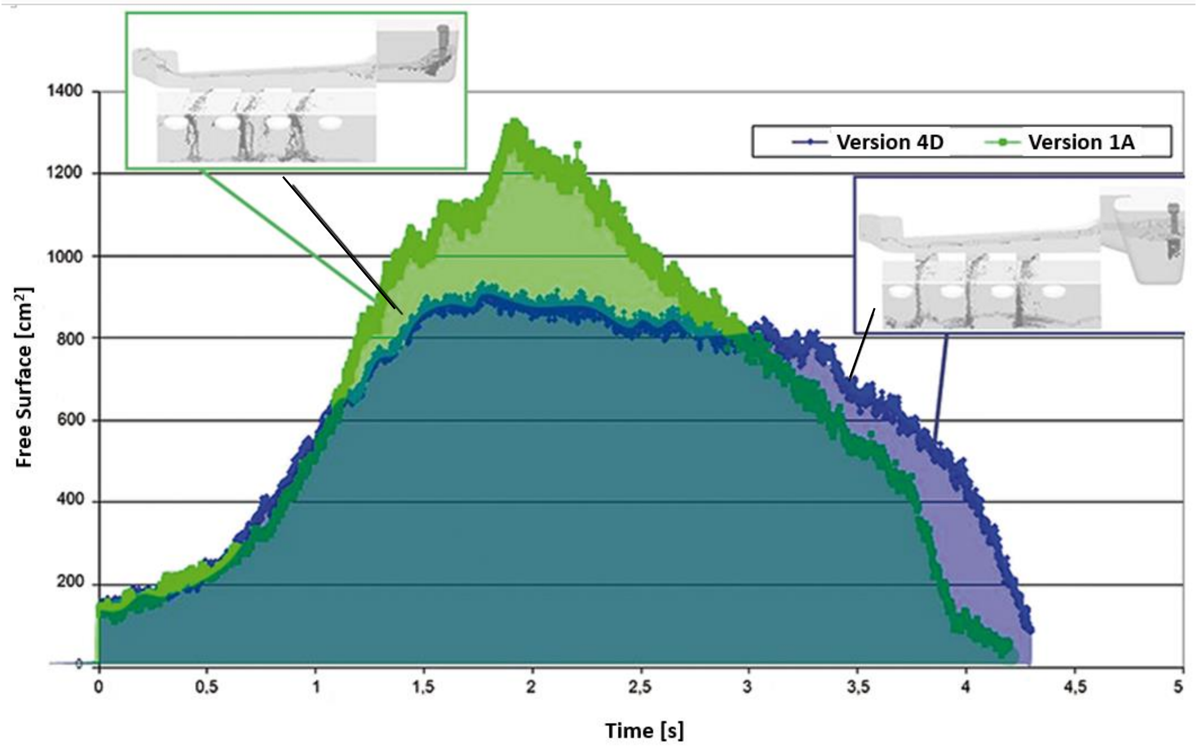


Fig. 20: Free melt surface as function of time for versions 1A and 4D.

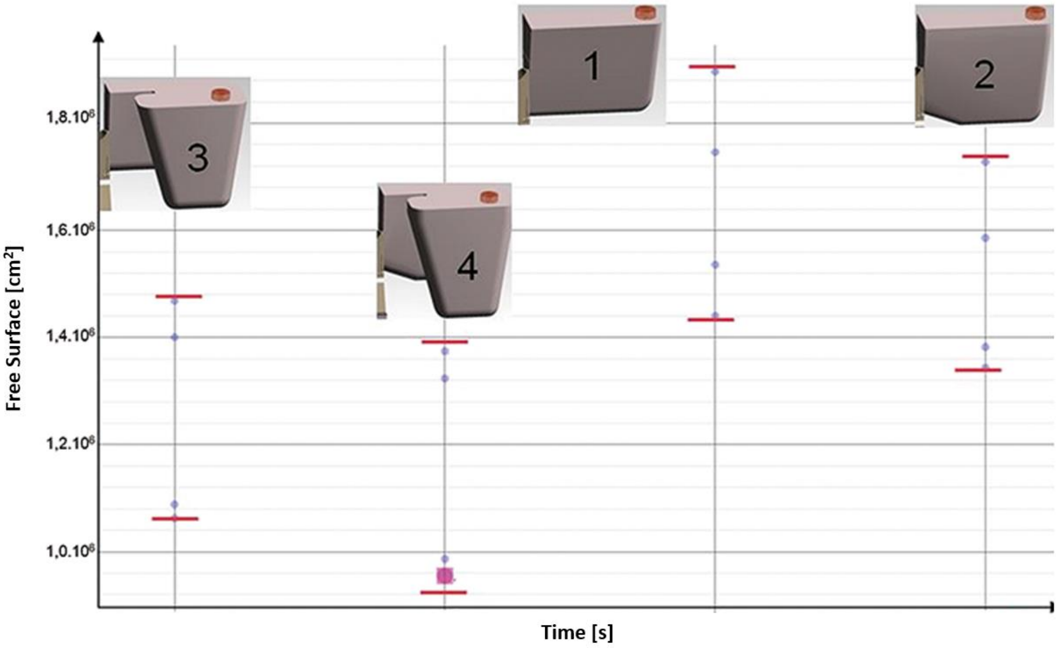


Fig. 21: Over entire mold filling process accumulated “free melt surface” [cm^2] for different pouring basin geometries and variations of its transition to the runner.

Evaluation of relationships between process parameters and goals

The significance of the relationships between the different modified process parameters and the evaluated goal functions can be displayed by the software through “main effect diagraphs” (figure 22) and easily evaluated.

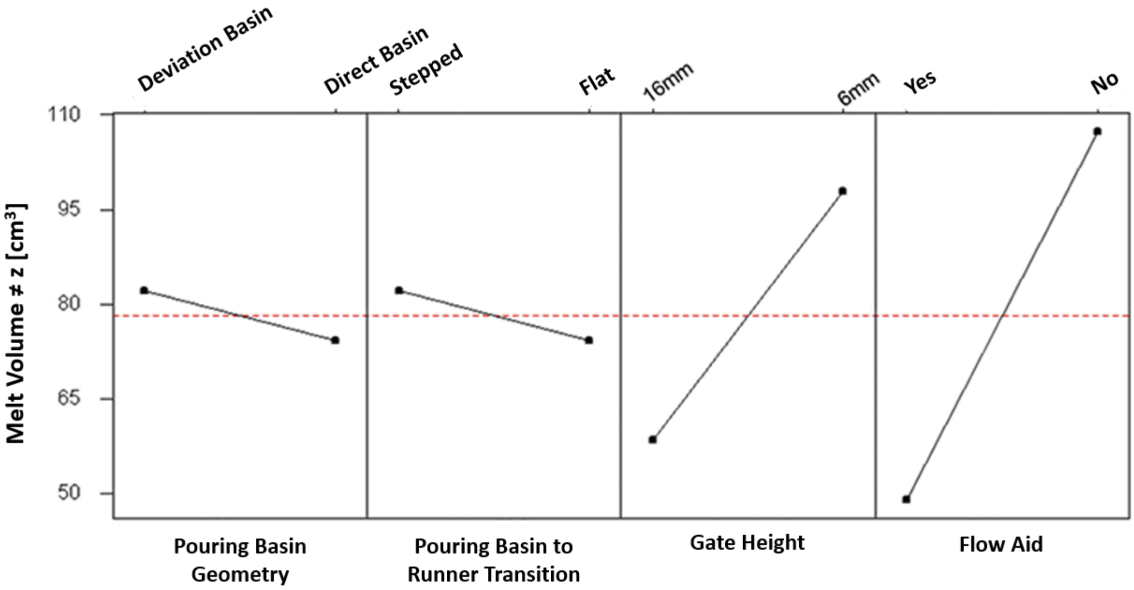


Fig. 22: The main effect diagraph of the impact of each variable on the goal function “melt volume with undesired flow direction” for gate A1

The y-axis displays the melt volume streaming through gate A1, which is not flowing in the desired flow direction. The lines show the impact of the four variables on the evaluated goal function. Shallow line angles in the windows for “pouring basin geometry” and “transition pouring basin to runner” indicate that these two parameters have only a small impact on this goal function. ”Gate height” and the “presence of filling aids” have a much bigger impact.

The impact of filling aids on the flow direction in the desired z-direction is shown in a scatter chart in figure 23. The cuts that are machined in have a significant impact on accomplishing the desired flow in z-direction.

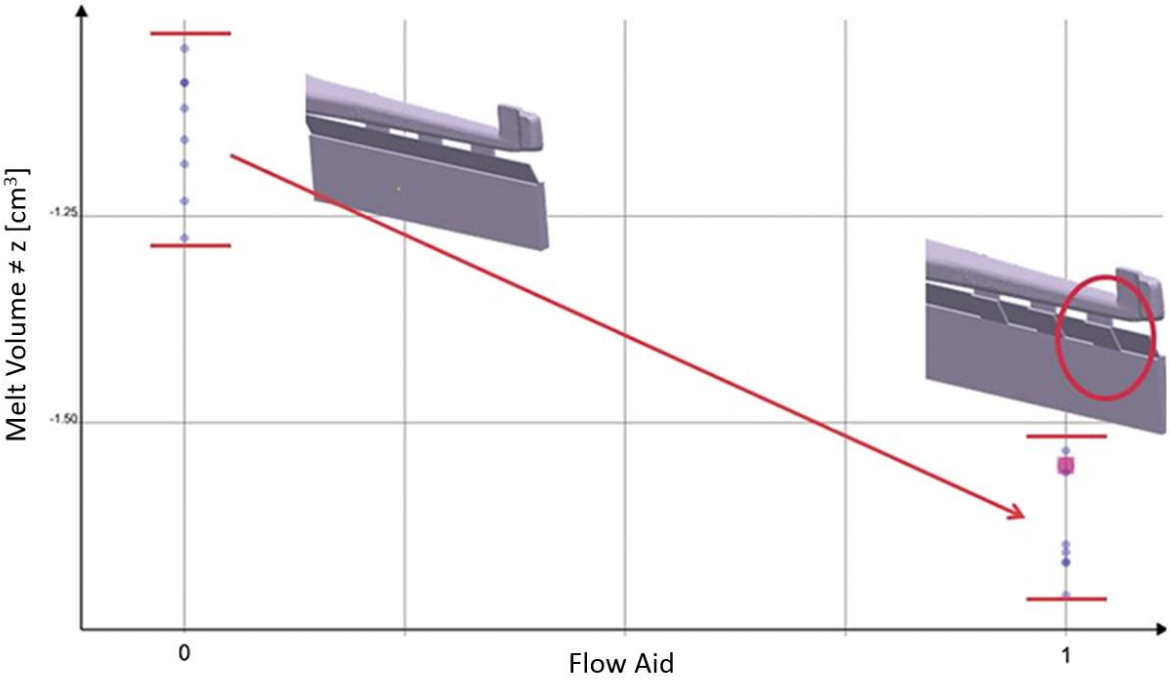


Fig. 23: Impact of flow aids on the melt volume flowing in the desired z-direction (0 = no flow aids, 1 = flow aids present)

In parallel to the discussed three goals, virtual particles (tracers) representing oxide particles already present in the melt and not created during the mold filling process, were evaluated. These particles were assigned the density of aluminum oxide and the typical size of oxide skins. The tracers move mostly due to flow dynamics inside the melt but also experience buoyancy resulting from the density difference between melt and oxide skins. As the final melt quality is strongly dependent on the transfer processes experienced by the melt before entering the mold, it was evaluated how significant the amount of entrained oxide particles is for each evaluated version.

The evaluation of the number of oxide particles inside the casting for the original version 1A and version 4D (best version for all other quality criteria) clearly shows the impact of the pouring basin geometry and its transition to the runner (figure 24). Even if the total amount of oxide particles in version 4D is larger due to its larger melt volume, less oxides enter the runner and the casting due to the optimized pouring basin design and the stepped transition between the deviation basin and the runner. The fraction of oxides inside the casting is cut in half coming from 11.7% down to 5.7%.

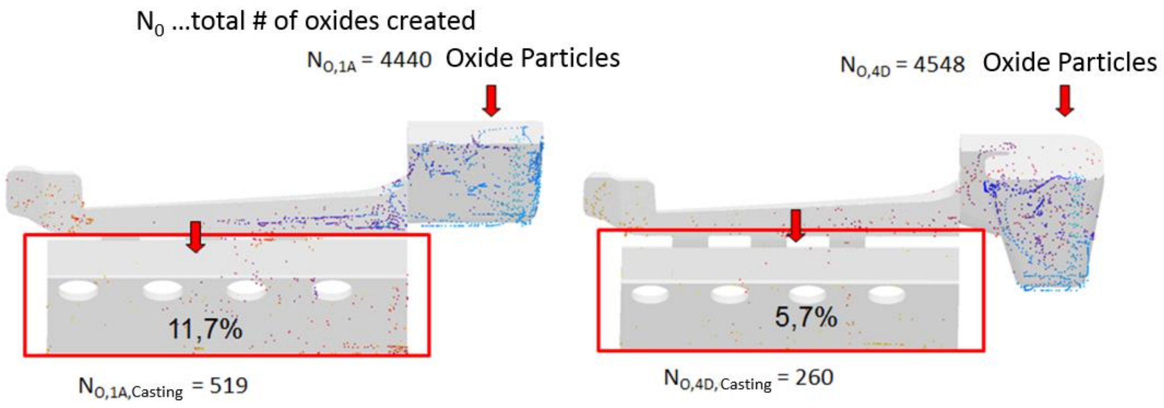


Fig. 24: Total amount of oxide particles N_o, total amount of oxide particles in casting $N_{o,Gussteil}$, and percentage value of oxide particles, which are found inside the casting at the end of the mold filling process (for versions 1A and 4D).

Comparison of simulation results with real castings

Version 4D is the best solution for all evaluated quality criteria to reduce oxide inclusions. Therefore, this version was implemented in a real world casting to compare it to the original version. Cylinder heads produced by both versions were examined using standard methods to find leakers. The statistical evaluation shows a clear reduction of oxide inclusion related leakers and confirms the validity of the chosen quality criteria (figure 25).

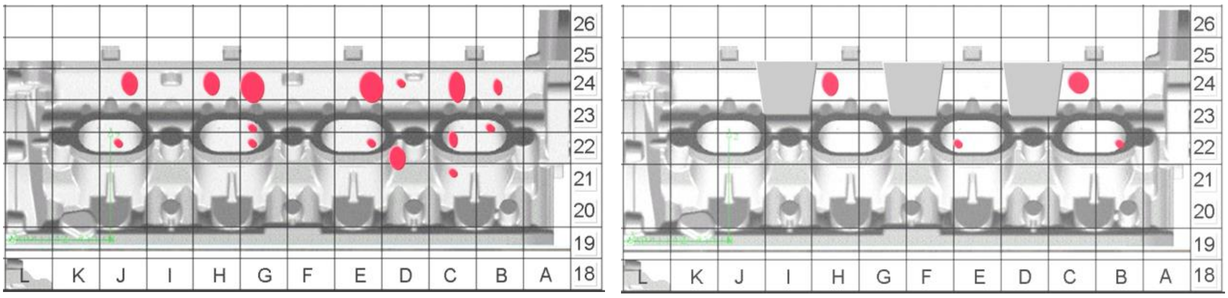


Fig. 25: Evaluation of leakers due to oxide inclusions of cylinder heads of version 1A (left) and version 4D (right). The red dots depict the location and frequency of leakers.

Summary

Casting process simulation was used to analyze potential sources for oxide creation during the semi-permanent mold casting process of cylinder heads. The experimental evaluation of the impact of melt transfer processes on melt quality using the PREFIL measurement method confirmed that the free fall of the melt during melt transfer processes and the related free melt surface turbulence bares a high risk for oxide creation. Using the filling of a pouring ladle as an example, it was shown how the integration of virtual DOEs in MAGMA^5 aids in varying process parameters to efficiently and quickly reduce the risk of oxide creation. It was demonstrated that through the utilization of the simulation tool MAGMA^5 and its fully integrated virtual design of experiments functionality, it is possible to efficiently evaluate ideas for the improvement of gating systems and process parameters early in the casting process development process for a new part. Beyond providing solutions for cylinder heads discussed in this paper, this new methodology provides comprehensive knowledge of quantifiable relationships between process parameters and quality criteria. This enables designers and foundry engineers to pursue several, even conflicting, goals at the same time.

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