Robust and Optimized Virtual Process Chain for Investment Casting

Investment casting has benefited many industries as an economical route to cast near-net-shape metal parts with high geometric complexity and dimensional accuracy. Nonetheless, the manufacturing costs and lead-times during production can quickly limit the competitiveness of investment casting as the preferred manufacturing route. Process simulation is the state-of-the-art tool for eliminating casting trials and improving casting quality, which significantly reduces production costs and time. It allows engineers to assess the technical feasibility of new components and to find the best compromise between casting quality and the production costs before creating costly physical prototypes. Using real industrial applications as examples, this paper will provide an overview of new developments and demonstrate current capabilities of the simulation software Magmasoft in addressing the entire process chain of investment casting virtually. In particular, it will discuss the benefits of Autonomous Engineering to the investment casting process, a new methodology for systematically investigating process windows by means of virtual Design of Experiments or autonomous optimization.

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1 Introduction

Investment casting is one of the earliest metal forming processes to produce complex castings to near-net-shape and in various materials. The technology has undergone a great evolution over time due to the need of precision components with complex geometries, driven by various industries. During the past decades, the investment casting industry has continued to expand not only due to the advantages it offers as a casting process, but also in manufacturing a variety of products. The goal of process design engineers in investment casting foundries is to set up a process that mainly meets three objectives:

> producing sound castings according to the specification,
> saving cost through high yields avoiding scrap and rework,
> establishing a robust process window in the first place.

The freedom to set-up an optimal gating and rising for the specific component and material is compromised by various processes and economically driven constraints such as the need to safely manipulate the wax cluster, limitations linked to coating and sanding and the need to apply as many castings to the tree as possible. Another challenge refers to the advantages of the process to be applicable to almost any cast material, especially those materials that have high melting temperatures or are aggressive in normal atmosphere. Accordingly, increasingly complicated parts are produced by investment casting from alloys that are more difficult to cast.

To meet today's specifications in producing high-integrity investment casting components, a profound understanding of the material behavior and the process robustness is required for the entire manufacturing route. The technology of simulating the casting process and predicting the resulting material properties has become a state-of-the-art methodology for foundrymen. Process simulation has shown to be an effective tool for investment casting pattern design allowing to accurately model defects and resulting properties for a wide range of casting alloys. Investment casting foundries have used simulation for many years to receive a confirmation (or the need for modifications) on their design decisions and process setup before the start of production of a high-integrity casting [1].

Magmasoft [2] allows the simulation and optimization of the investment casting process taking into account all essential process steps and thermal boundary conditions. The software offers dedicated functionality to address the specifics of the process not only for the core process of filling and solidification. Prediction of microstructures and resulting mechanical properties and prediction of stresses, cracks and distortion for the as-cast part or after heat treatment enable you to make reliable design decisions and to establish a robust process window before performing real experiments (**Figure 1**). This paper discusses basics and major influencing parameters of the heat flow in the investment casting process. The innovative methodology of Autonomous Engineering is using a systematic variation of influencing process or design conditions in a virtual Design of Experiments. Its benefits for investment castings are presented for various industrial applications. This allows modeling the impact of critical parameters such as dif-

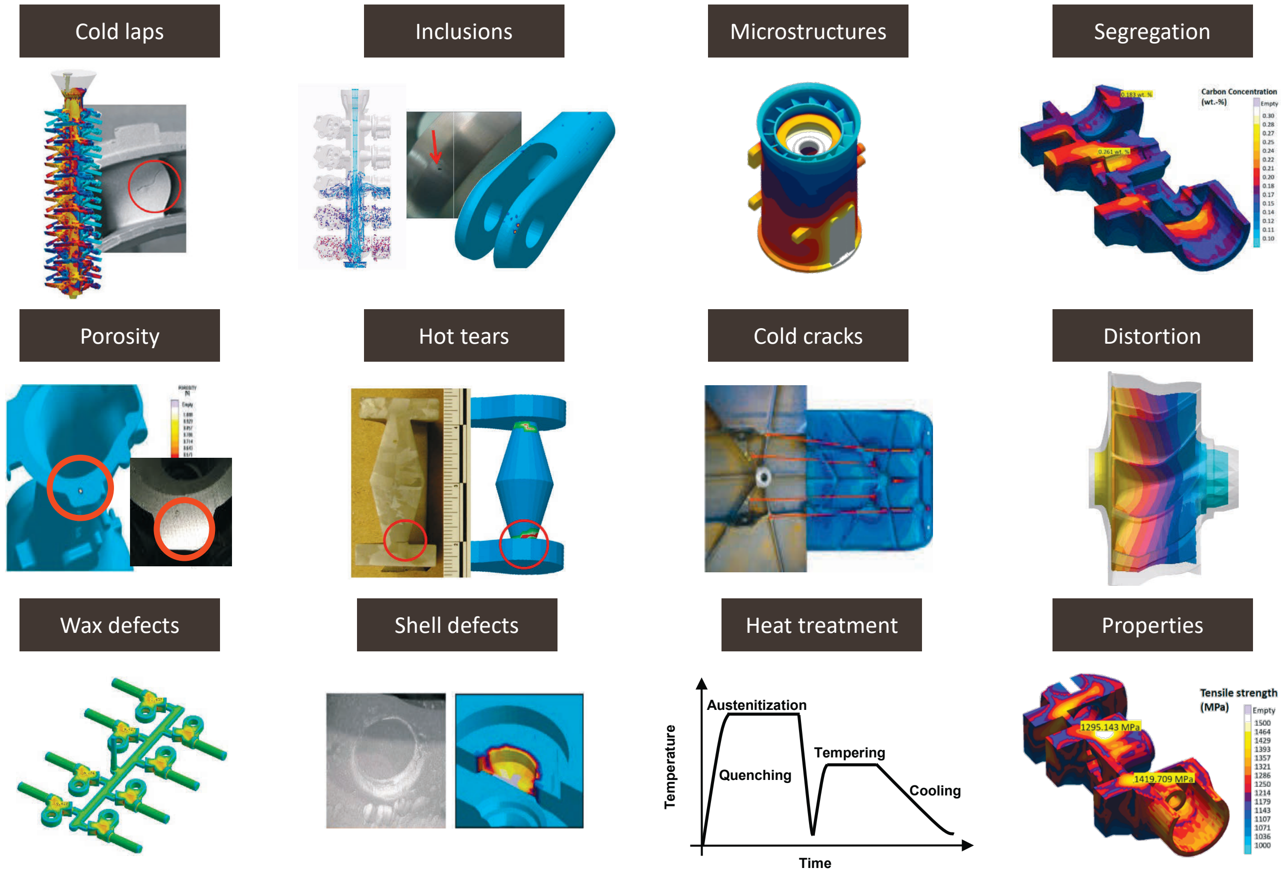

Figure 1: Simulation and prediction of different quality issues in investment casting.

ferent shell materials, modifications to the pattern design or gating system, or process variations such as pouring time and temperature. The effects of these systematic variations on the resulting fluctuation of quality criteria in the casting are evaluated. Applying these developments, investment casting foundries leverage their casting engineering and process setup to a new level. It allows them to realize new, robust and optimized solutions and reliable manufacturing routes before the production of a high-integrity casting has started.

2 Thermal process requirements

When molten metal is poured into a preheated investment casting shell, solidification takes place already during filling. Its extents depend on the applied superheat of the melt, the shell temperature and the thermo-physical properties of the alloy. Once mold filling is completed, the transient temperature distribution in the melt is driven by conductive and convective heat transport. The heat in the melt is transferred to the mold through the solidifying metal. At the same time, the contracting casting results in a growing gap and related heat resistance to the mold. The resulting thermal contact and related heat transfer coefficient (HTC) between the casting and the mold is a function of time and pressure (shrinkage), the surface tension of the liquid metal, gases precipitated in the gap as well as the roughness of the investment casting shell.

Depending on the ambient conditions and the temperature level at the mold surface, the heat is further transported by combined convection and radiation. For most investment casting processes, the radiative exchange between different mold surfaces and to the surroundings must be considered (**Figure 2**) [3]. To accurately simulate the solidification process, reliable and realistic data on the thermal properties of the investment casting shell (thermal conductivity, specific heat capacity, density and shell permeability) are required (**Figure 3**) [4]. An investment casting shell is a mixture of several ceram-

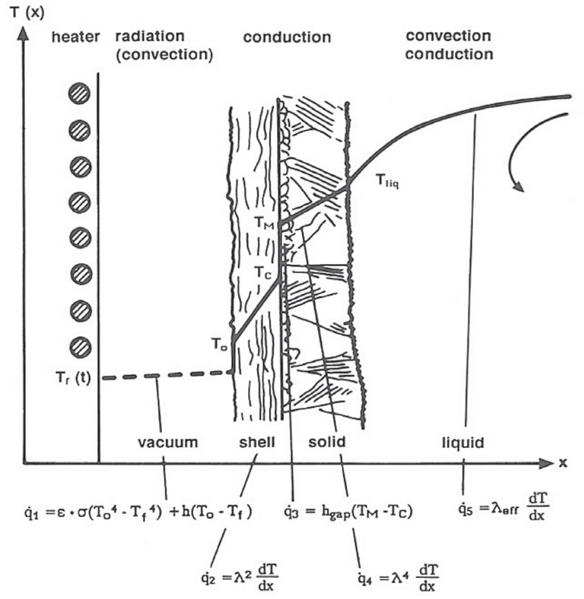

Figure 2: Major heat transport mechanisms in investment casting [3].

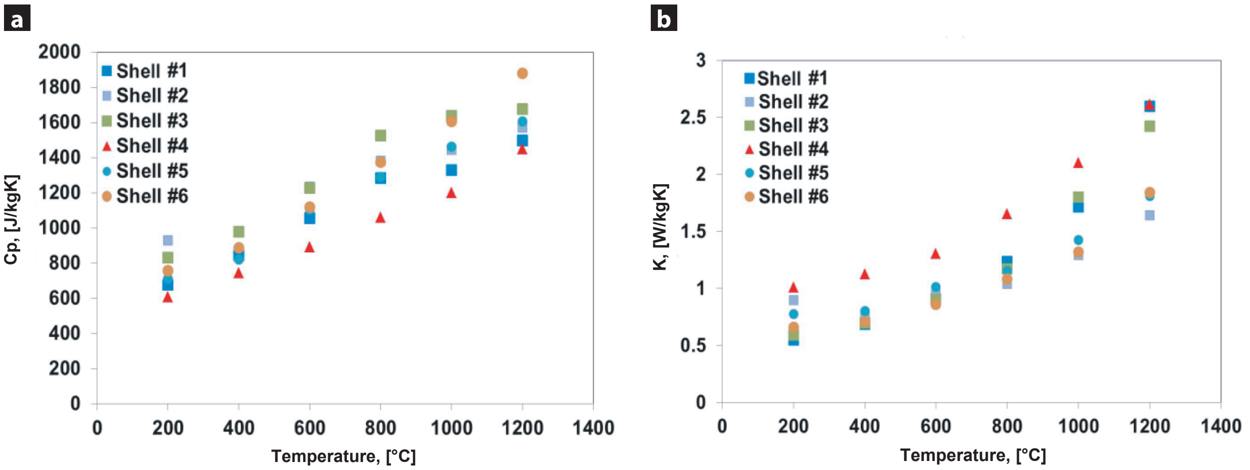

Figure 3: Variation of thermo-physical properties of shell molds as a function of temperature for different shell types. a) heat capacity Cp, b) thermal conductivity K [4].

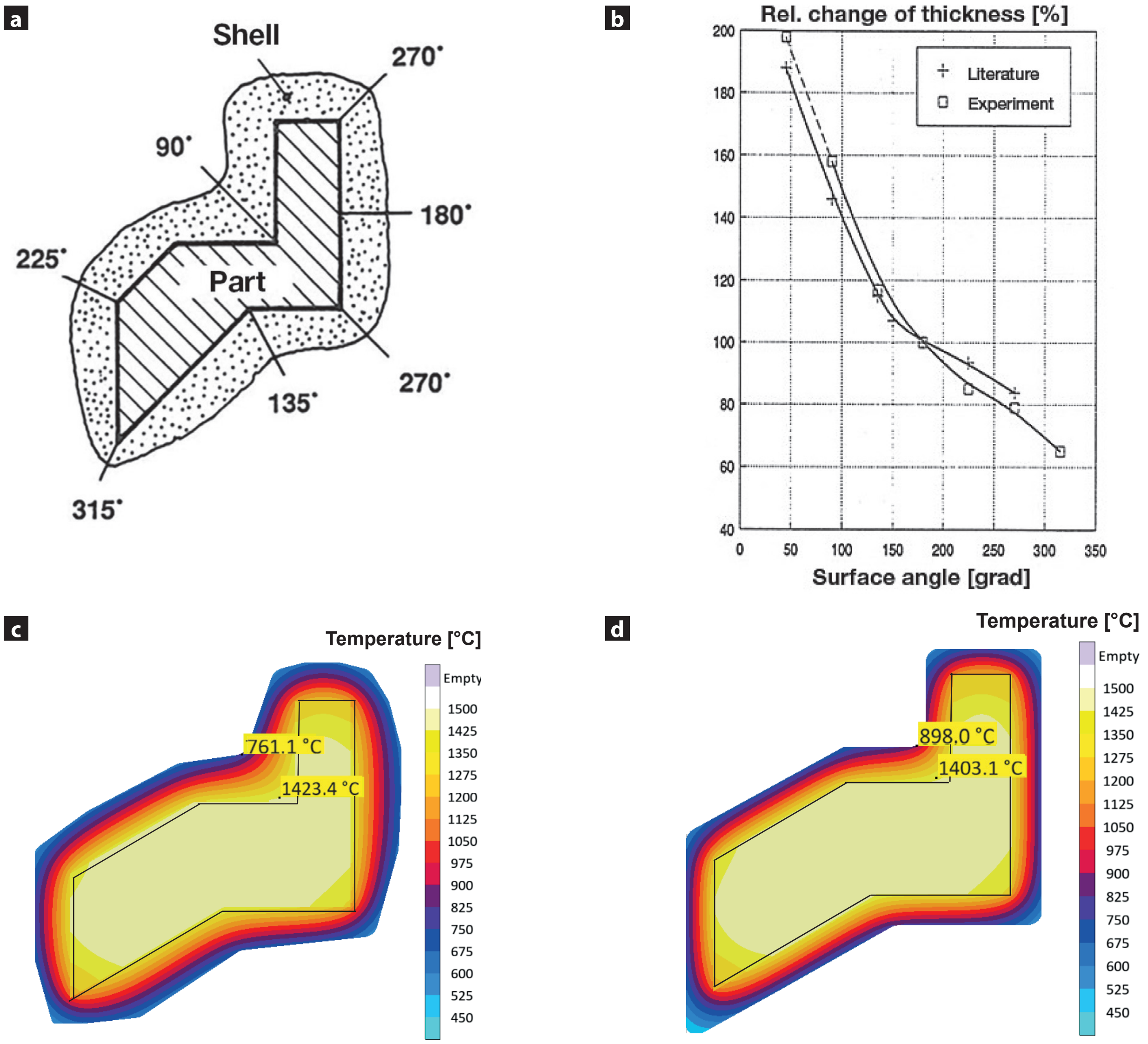

Figure 4: a, b) Shell mold thickness as a function of the local surface contour and coating process [3]. c, d) Comparison of the temperature distribution between "real" and "uniform" shell thickness for a given time.

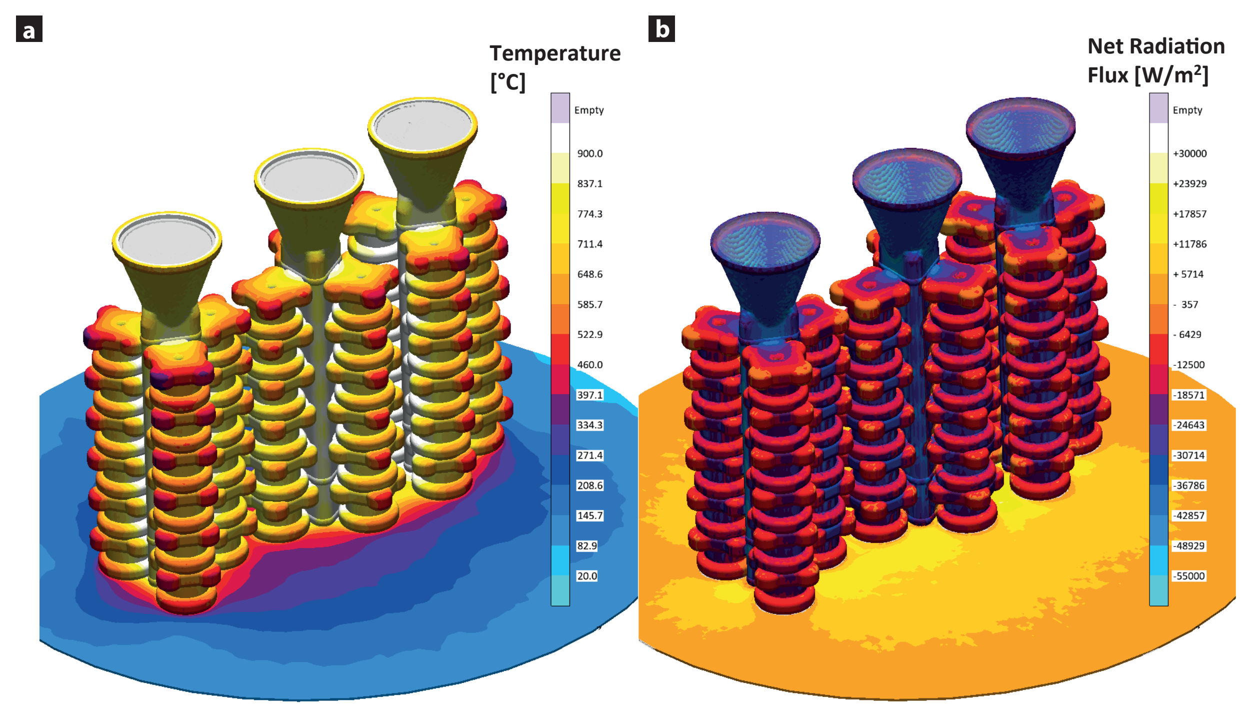

Figure 5: Influence of radiative heat exchange of the shell mold on the casting cooling; a) the local temperature distribution and b) net radiation flux at a certain time show significant difference of inner and outer surface areas.

ic constituents that are exposed to several thermal processes (drying, heating up to remove wax pattern, sintering and pre-heating before pouring).

2.1 Impact of the investment casting shell on the heat flow

The precondition for a quantitative prediction of the solidification and resulting part quality using casting process simulation is an adequate consideration of the ceramic shell as the major heat sink and thermal barrier. This means besides the knowledge of accurate thermo-physical data for the heterogeneous shell material, the local thickness of the shell must be known. The local shell thickness is dependent on the coating and sanding processes (number of sanding layers, grain size and slurry rheology), but is also related to the part geometry. In inner corners, the ceramic slurry as well as the sand accumulates whereas on outer surfaces and corners both tend to be washed off. The resulting shell thickness in the simulation model can be addressed as a function of the local surface angle considering 180 °C as a flat surface (**Figure 4**).

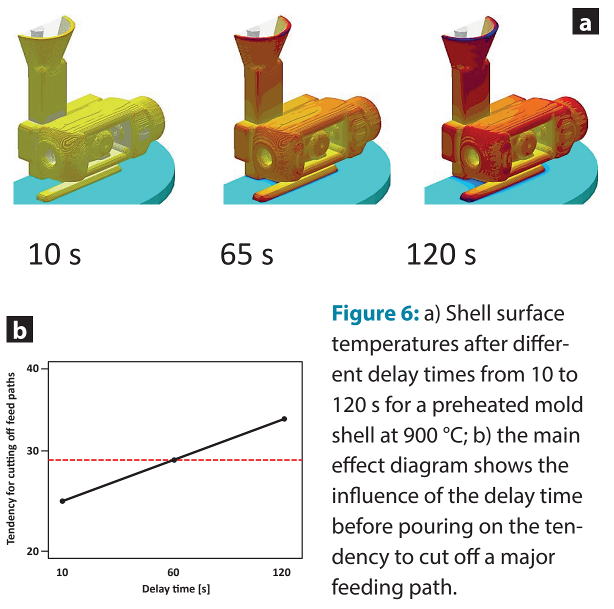

Figure 6: a) Shell surface temperatures after different delay times from 10 to 120 s for a preheated mold shell at 900 °C; b) the main effect diagram shows the influence of the delay time before pouring on the tendency to cut off a major feeding path.

2.2 Consideration of thermal radiation from the shell

The entire heat that is moving through the shell mold needs to be further transported to the surrounding. In this respect cooling is determined by the total heat emission from the shell mold driven by radiative, conductive and convective transport. However, for casting under ambient conditions, the heat transport in the air due to conduction and convection is limited due to its linear relation to temperature differences. Radiation is usually the dominant heat transfer mechanism in an investment casting process. The heat flow is dependent on the emission coefficient of the ceramic surface and increases by the power of four with the temperature difference between emitting surfaces of the preheated mold and the surroundings. In the case of a casting under vacuum, radiation obviously becomes the only transport mechanism.

The degree of heat emission depends to a large extent on the local radiation conditions. This means that the heat emission is larger on surfaces with free emission to the surroundings than it is for surfaces where the radiation is limited due to surfaces exchanging heat with other parts of the shell mold. The amount of radiative exchange is defined by view factors that describe the orientation of different surfaces to each oth-

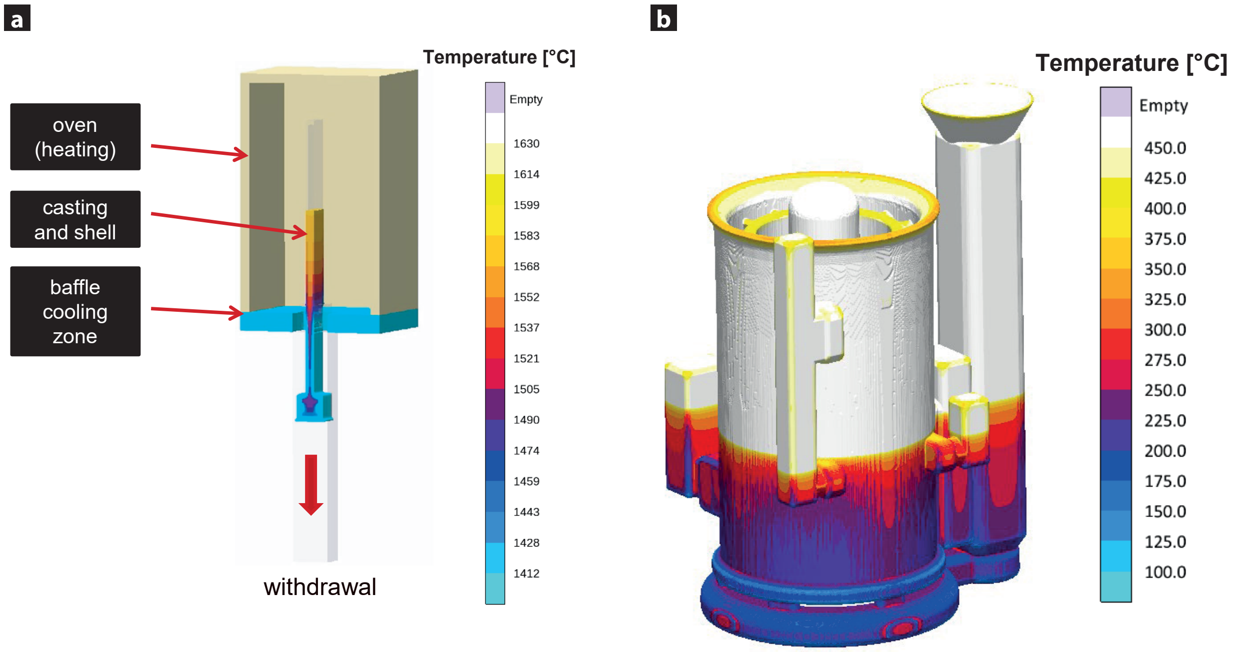

Figure 7: Controlled cooling and solidification due to defined heat sinks; a) directional solidification in a vacuum furnace with defined heating and cooling zones; b) Fast cooling of the shell in a controlled way.

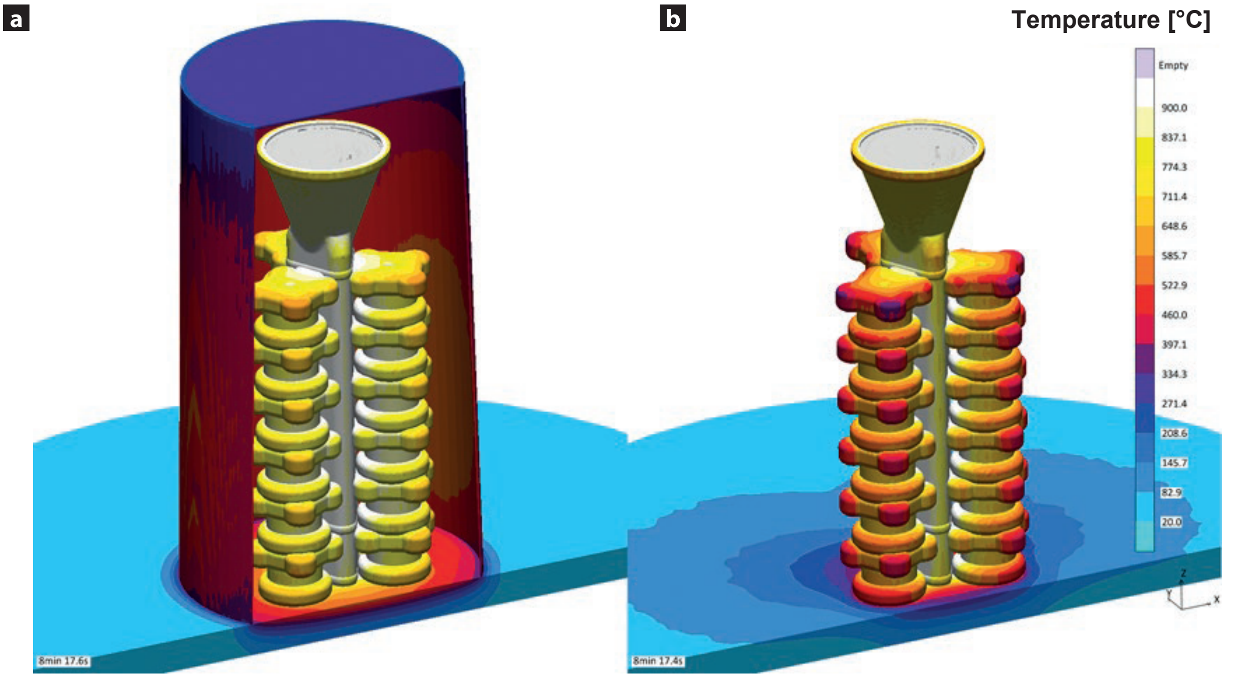

Figure 8: Comparison of shell surface temperatures for a) canning and b) free cooling at the same time.

er [3]. To solve this computationally intensive issue effectively, modern ray tracing algorithms have been developed [5]. The example shown in **Figure 5** illustrates the influence of radiative exchange and shadowing of the shell mold for an assembly of three investment casting shells. The inner surfaces of the shell stay hotter than the outer areas due to reflected heat from the central runner, which is the last to solidify.

2.3 Influencing the cooling of the shell before and during casting

Time delays due to transport of the shell from the firing furnace and further preparations can lead to significant cooling of the shell at the time of pouring and may influence the solidification accordingly. **Figure 6** shows the surface tempera-

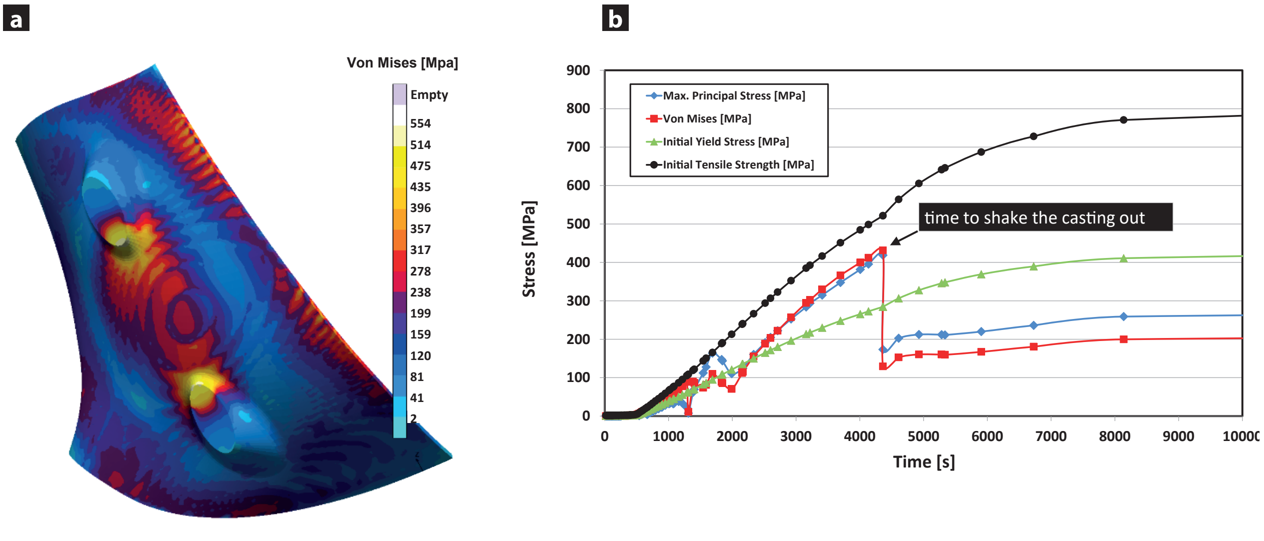

Figure 9: a) The von-Mises stresses on the backside of a turbine blade show high stress levels in the area of the gates; b) development of von-Mises stress during solidification and cooling.

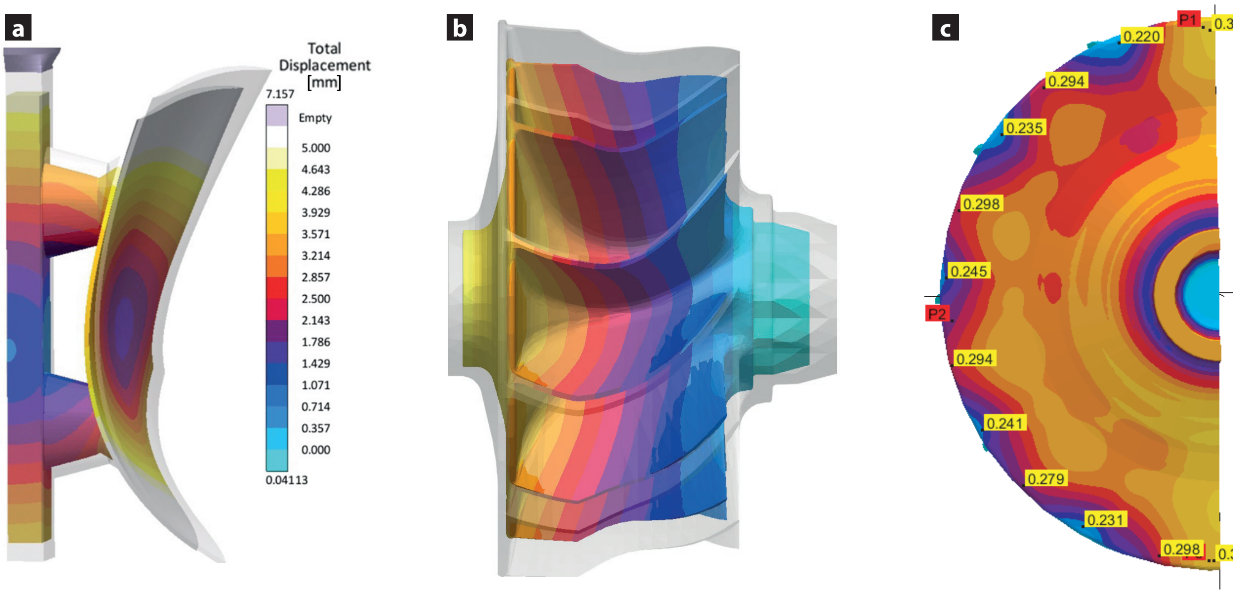

Figure 10: Linear shrinkage and part distortion (exaggerated) compared with the original geometry for a) a turbine blade and b) a turbine wheel; c) quantitative assessment of part distortion in a virtual CMM device.

tures of the shell for different delay times from 10 to 120 seconds. The initial temperature of the shell is 900 °C. In investment casting, various routes to control the heat flow during the casting process have been developed. The well-known Bridgman process is used to realize directional solidification within the casting by moving the casting in a vacuum furnace from a heated to a cooled zone. This process is mainly used to realize single-crystal turbine blades (**Figure 7** a).

For complex aluminum investment castings, different processes to control the cooling power and cooling direction have been developed (e. g. Sophia, Elite processes). A computer-controlled process lowers the entire shell into a cooling medium after casting. The quench conditions are matched with the component's geometry and lead to a controlled and faster solidification and finally to improved microstructures, (Figure 7 b). In investment casting, it is common to cover the shells after pouring (canning). This allows influencing the heat transfer from the shell to the surroundings and consequently affecting the cooling rate of the castings. **Figure 8** compares the surface temperatures of the shells in the case of using canning and free cooling.

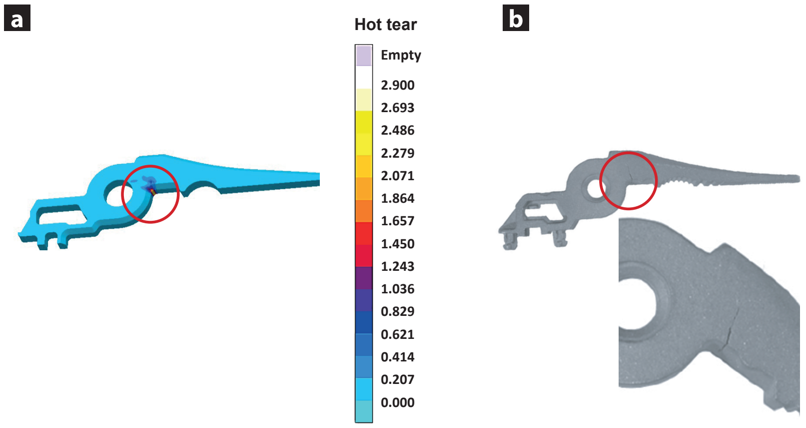

Figure 11: Stress simulation; a) indicating hot tear risk in pliers for defined process conditions and b) comparison to real findings [7].

3. Investigating stresses, cracks and distortion

The casting shrinks during cooling. Depending on inhomogeneous cooling, different thermal expansion properties and constraining due to the mechanical resistance of the shell, plastic deformation takes place, resulting in residual stresses in the casting. Casting distortion and, in extreme cases casting cracks are a detrimental consequence [6]. Cold cracks may occur if von-Mises stresses exceed the local tensile strength at a given temperature (**Figure 9**). The von-Mises stress level at 400 °C is shown on the back of a turbine blade. The von-Mises result showed some high stress levels near the gates on the backside of the turbine blade. Plastic deformation can be expected, as the von-Mises stress (red line) exceeds the yield strength before the casting shake out. In no case are cracks predicted as the stresses do not reach the tensile strength (black line) at any time.

When stresses evolve during casting and cooling, this must lead to part distortion. Due to the rigidity of the shell, plastic deformation in the casting results in part distortion, especially after shake out. **Figure 10** shows two examples of volumetric contraction and part distortion of a turbine blade and an impeller casting after solidification and cooling. Virtual coordinate measurement capabilities (CMM) enable the quantification and comparison of the local distortion for different designs.

Hot tearing is a major stress related defect in investment casting foundries causing costly repair welding or even scrap. The root causes for tearing are thermal gradients and constrained contraction due to the ridged shell resulting in straining during solidification, insufficient feeding and the metallurgical state of the melt. Integrated solidification and stress modeling allow investigating possible measures to avoid hot tearing. The example in Figure 11 shows the comparison of the predicted hot crack risk with the real findings in the casting.

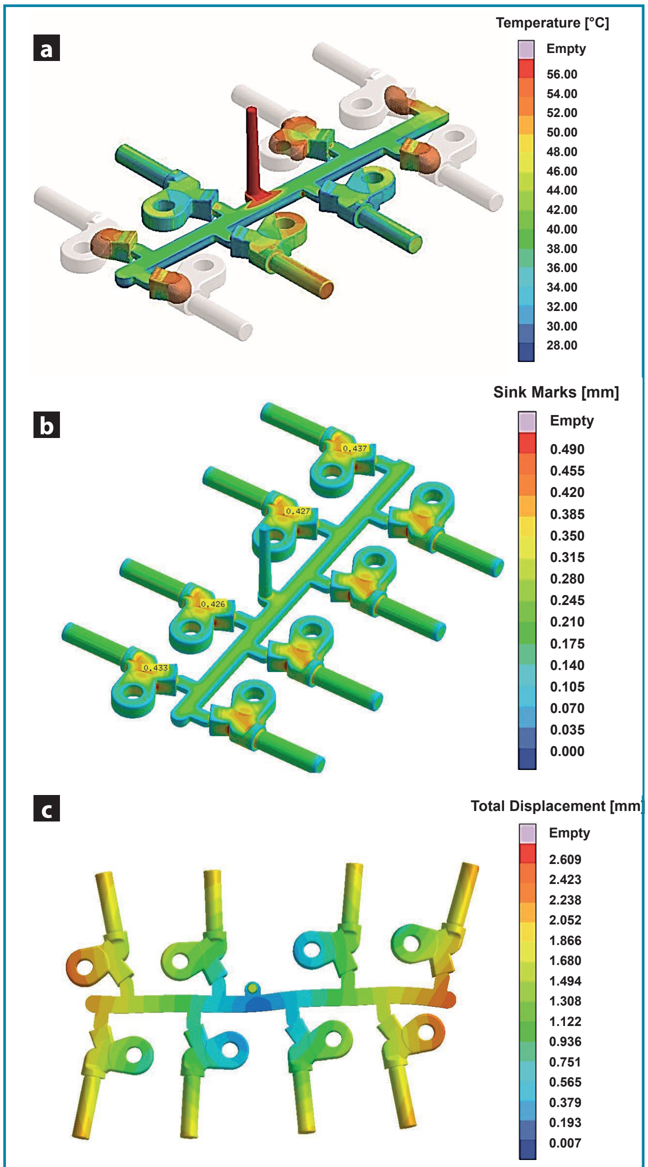

Figure 12: Simulation of the wax injection, indicating a) unbalanced filling, b) sink marks due to insufficient pressures, c) distortion of the pattern [8].

4 Addressing the entire process chain

4.1 Wax injection

Investment casters are always aiming to optimize production times and costs over the entire casting process. Therefore, interest has grown in simulating other part processes in investment casting. Looking upstream in the investment casting process chain, the use of simulation to investigate the production of wax patterns is very interesting [8]. Many defects created during wax injection will be found in the final casting if they are not detected earlier. A significant percentage of scrap is a direct result of poor wax patterns, e. g. surface defects, entrapped gas and core breakage. Understanding the wax behavior and being able to model the filling in complex geometries is the first step toward the understanding of this important stage of the investment casting process. Sigmasoft [9] is a plastic injection simulation software package that enables addressing the non-Newtonian flow nature of investment casting waxes. Figure 12 shows the simulation of a wax injection. With an initial injection temperature of 56 °C, the wax cools down to 19 °C during filling. At the end of injection, the wax temperatures vary up to 25 °C. This leads in an unbalanced filling resulting in sink marks and distortion.

4.2 Heat treatment, microstructure and material properties

On the down-stream side of the process chain many steel as well as non-ferrous investment castings require a heat treatment following the casting process. The objectives are either to obtain desired microstructures as well as mechanical properties or to reduce existing residual stresses and part distortion. Process simulation can predict microstructures and resulting mechanical properties as a function of the chosen heat treatment process conditions.

Magmasoft predicts the local segregation of alloying elements during solidification. By using this information in subsequent heat treatment simulations, it is possible to consider the influence of local concentration differences on the microstructure distribution as well as the material properties after heat treatment. **Figure 13** shows the impact of carbon segregation on the local martensite formation after quenching for two regions of a steel casting (geometry see figure 17) with similar cooling rates during the quenching process. During heat treatment, the stress state of the casting changes completely. During annealing (normalizing or solution treatment), the stress relief in the casting is governed by plasticity and creep effects. During quenching, stresses are built up strongly, driven by high temperature gradients. Also density changes in the cast part, which increases crack risks during quenching. As the cooling rate increases, the martensite fraction in the microstructure increases too, resulting in a change in local density, which means non-uniform volumetric contraction in the microstructure. To minimize part distortion and crack risks, it is necessary to establish a good compromise between material characteristics and tolerable stress levels.

5 From simulation to Autonomous Engineering

In metal casting processes, everything happens at the same time and is closely coupled. While this can be regarded as a key advantage of metal casting in comparison to other manufacturing processes, it also makes decision-making regarding an optimal process layout complex. Changing only one process parameter can influence the final casting quality in many ways. This makes it challenging to manually optimize the casting process in the real-world by simultaneously pursuing quality and cost objectives [9, 10]. The complex interactions related to the number of variables that exist in the casting process are the root cause for various quality defects. **Figure 14** displays a simple cause and effect diagram for the investment casting process showing the diversity of different variables influencing the casting quality.

Due to the diversity of factors that affect casting quality and the complex interactions between physics, metallurgy and casting geometry, even the expert knows neither the possible optimum nor the robustness of the process window chosen prior to a multitude of trials. A new approach overcomes these limitations. This methodology, called Autonomous Engineering, utilizes multiple simulations with Magmasoft as a set of virtual experiments in order to achieve the best possible solutions. Autonomous Engineering uses the simulation tool as a virtual experimentation or test field. By changing the casting technology of investment casting, e. g. the gating and risering design or manufacturing parameters, the software aims to find an

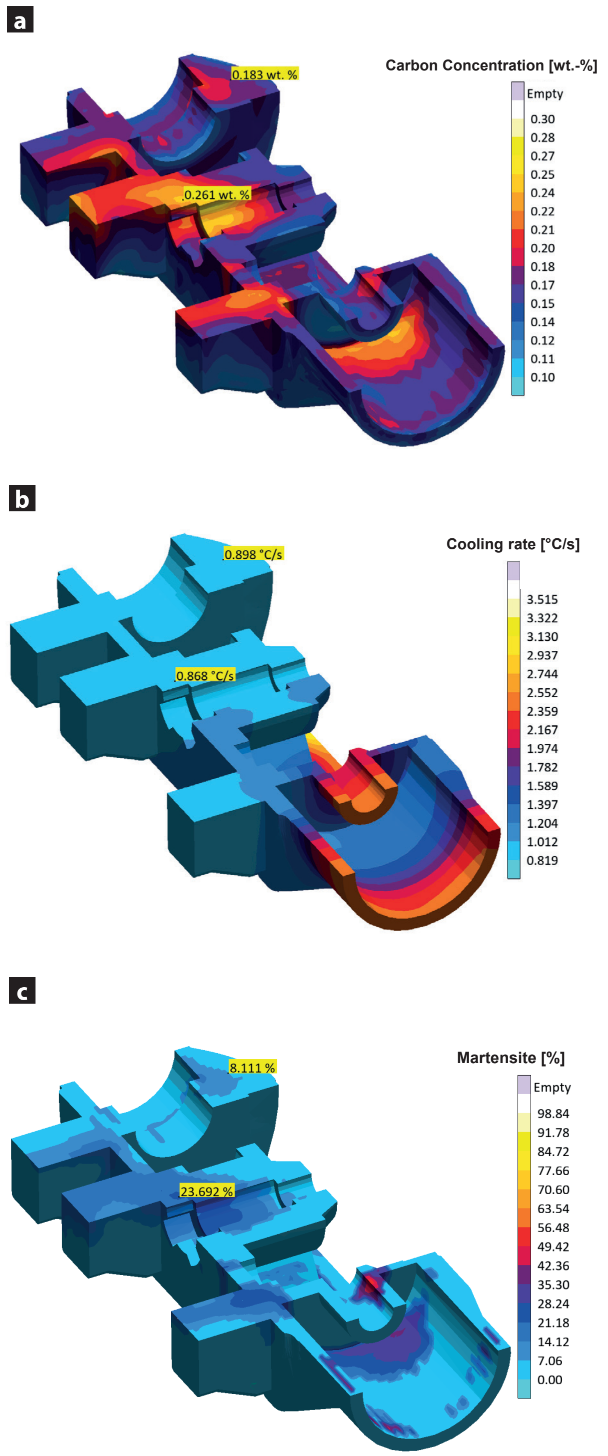

Figure 13: Effect of carbon segregation on martensite formation during quenching. a) Differences in carbon content due to segregation in the casting process, b) local cooling rates during the quenching process, c) differences in martensite content in two regions after quenching despite identical cooling rates.

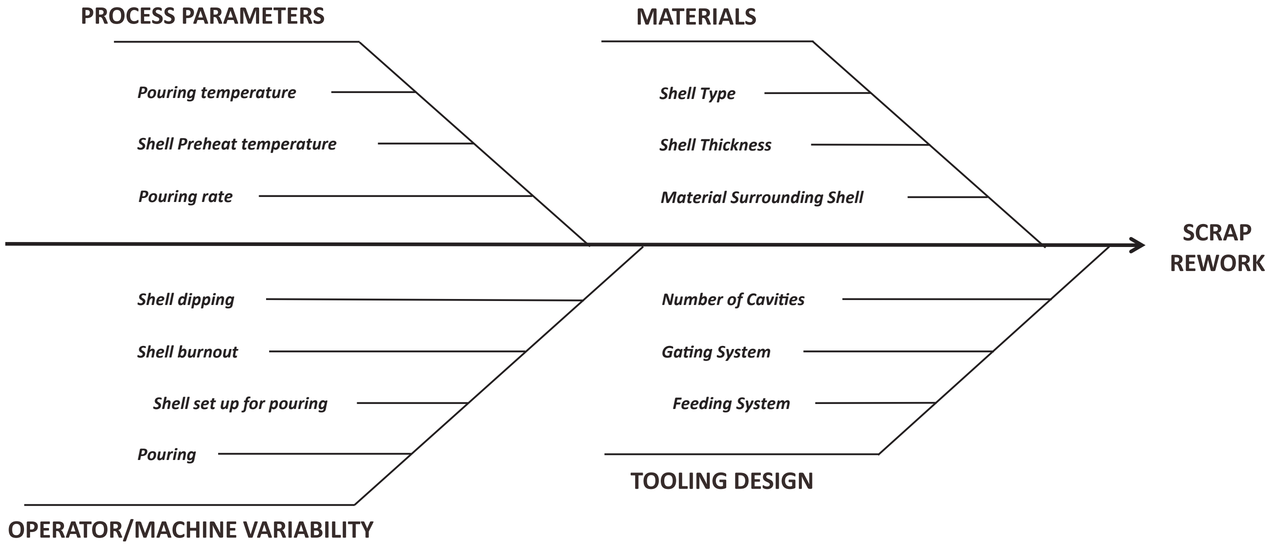

Figure 14: Cause and effect diagram for the investment casting process: Different variables are influencing the casting quality [7].

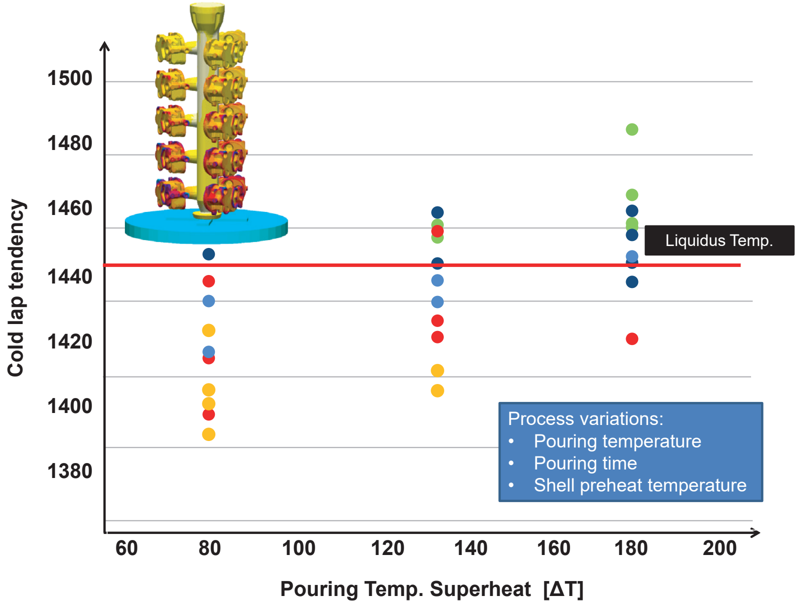

Figure 15: Cold lap tendency as a function of the superheat of the melt for various process variations.

optimal operating point within the specified limits. Several parameters can be systematically modified at the same time and can be evaluated independently from each other. In addition, the process robustness can be assessed before the first casting is done. The software uses statistical approaches (Design of Experiments / DoE) pursuing several targets simultaneously and finds the best compromise based on first principles [9]. The automated assessment of all simulated quality criteria can be used to quickly and easily find the optimal route to achieve the desired objectives. In addition, the number of real-world trials can be reduced, and the impact of various process parameters on reaching a robust process window can be assessed in early phases of casting, pattern and process development. The methodology of Autonomous Engineering is not a replacement for process knowledge and expertise of the foundryman. Based on the technical and economical boundary conditions for their process, the foundry engineers need to specify which parameters they may change and to what extent. This is done in combination with the requirements placed on the casting and the objectives to be achieved. Quantitative descriptions of the important influencing factors, measurable quality and cost indicators, and the objectives are required to answer these questions. Applying these developments as an integral part of Autonomous Engineering, this is a unique opportunity for investment casting foundries to achieve new and optimized applications as well as reliable manufacturing routes before the production of a high-integrity casting has begun.

5.1 Robust process conditions - effects of process parameters

The term 'robust' means capable of performing without failure under a wide range of fluctuating process conditions that cannot be controlled. The process variability in investment casting is a significant issue. The main variables affecting castability in investment casting are pouring temperature, pouring rate, shell temperature and shell thickness. The pouring temperature is dependent on the given alloy, geometry and process conditions. High pouring temperatures can cause gas pickup of the melt or undesired metal-mold reactions. In contrast, low pouring temperatures can lead to cold laps or even unfilled areas in thin-walled castings.

In the following example, a virtual DoE was performed for the following process variations:

> Shell temperatures (900 to 1100 °C)
> Pouring temperatures (1530 to 1630 °C)
> Pouring times (7 s, 10 s, 13 s, 16 s)

In total, a full factorial DoE with 36 virtual experiments (filling and solidification) was done. **Figure 15** displays the results for all virtual experiments in a scatter diagram. The results for the cold lap tendency are drawn over the variable superheat. The cold lap danger is obviously growing with lower pouring temperature. Due to the impact of the other variables (shell temperatures, pouring times) the figure shows a scatter of results for any pouring temperature chosen. This indicates that process robustness is growing with lower superheat.

Figure 16 shows the correlation of the three further important process parameters influencing the casting quality, here on volume and microporosity in the casting. As mentioned earlier, it is not only important to visualize the variability of one parameter, but even more informative to show the interaction with other process parameters when one parameter is changed. While the pouring temperature has only a marginal impact on the final porosity, shell temperature increases especially have a detrimental influence on micro-porosity, whereas a longer pouring time reduces volume shrinkage.

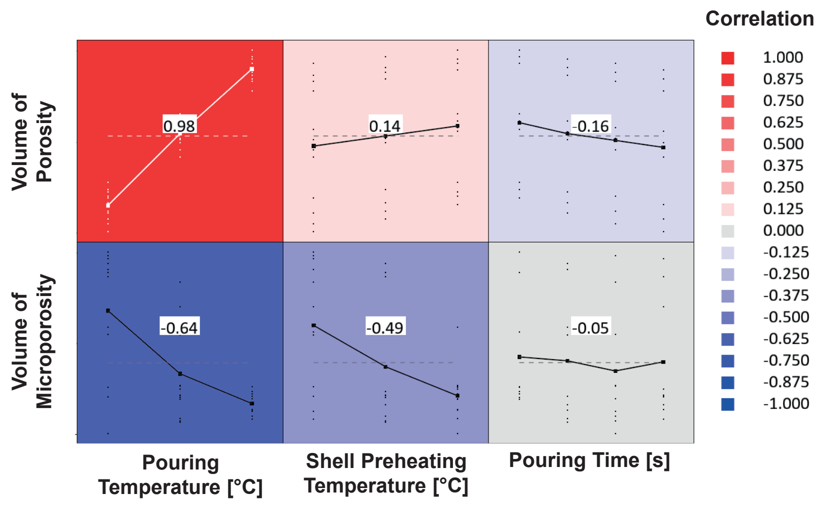

Figure 16: Correlation diagram showing the impact of pouring time, shell temperature and pouring time on the volume of macro- and micro-porosity.

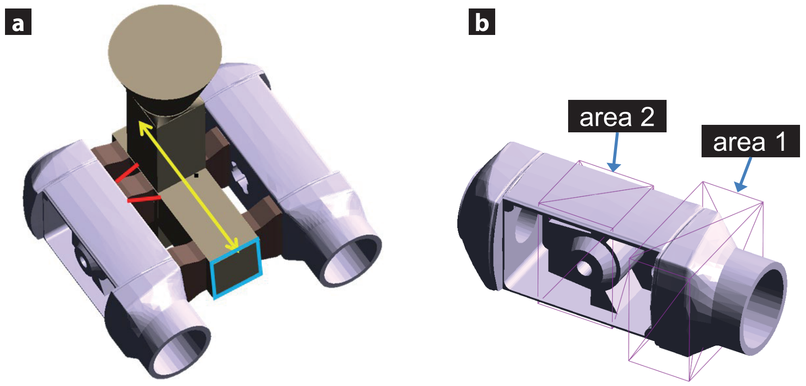

Figure 17: Parametric variation of runner and gate dimensions to improve the feeding path into the casting. a) Variables: runner cross-section (blue), changing down sprue position (yellow) widening gates (red). b) Evaluation areas to assess the quality criteria during solidification in critical sections of the part.

5.2 Robust casting engineering,

A sound and quality casting is highly dependent on its methoding. During engineering, the layout and dimensioning of gating and risering has a direct impact on the cast part quality. The majority of casting defects can be avoided with an optimized gating and risering system, mostly paying the price of reducing yield or increasing manufacturing costs.

5.2.1 Improving feeding by adjusting runner and gates

The design of efficient gating- / feeding systems for investment castings has always been difficult due to a number of limiting factors, resulting from the complex geometries and the process needs. In the following case multiple gating concepts were investigated with virtual DoE using parametric geometries for the following variations of runner/down sprue:

> Cross section of runner/sprue (blue line, 5 variants),
> Sprue position (yellow line, 7 variants),
> Gate width at runner junction (red line, 3 variants).

The software autonomously evaluates a full factorial DoE with 105 different designs and then simulates filling and solidification for all possible combinations. Without any interaction of the user, each simulation in the autonomous DoE is set up, calculated and automatically assessed based on the chosen quality criteria. The user defines the main objectives here to find the best compromise between all variants to realize an optimal feeding path in the casting. The influence of the gating design on minimizing the hotspot volume for a given fraction solid is investigated in certain critical areas (**Figure 17**). **Figure 18** shows the results of the virtual DoE to evaluate the impact of different gating concepts on hotspots and shrinkage porosity defects. The parallel coordinate diagram helps to gain a better understanding of the impact of parameter changes on an improved feeding path in the casting for the selected quality criteria.

5.2.2 Runner configuration for optimized melt cleanliness

To avoid quality scatter, a main issue in the design of a gating system for investment castings is to make sure that all cavities are filled and solidify evenly. From the process point of view,

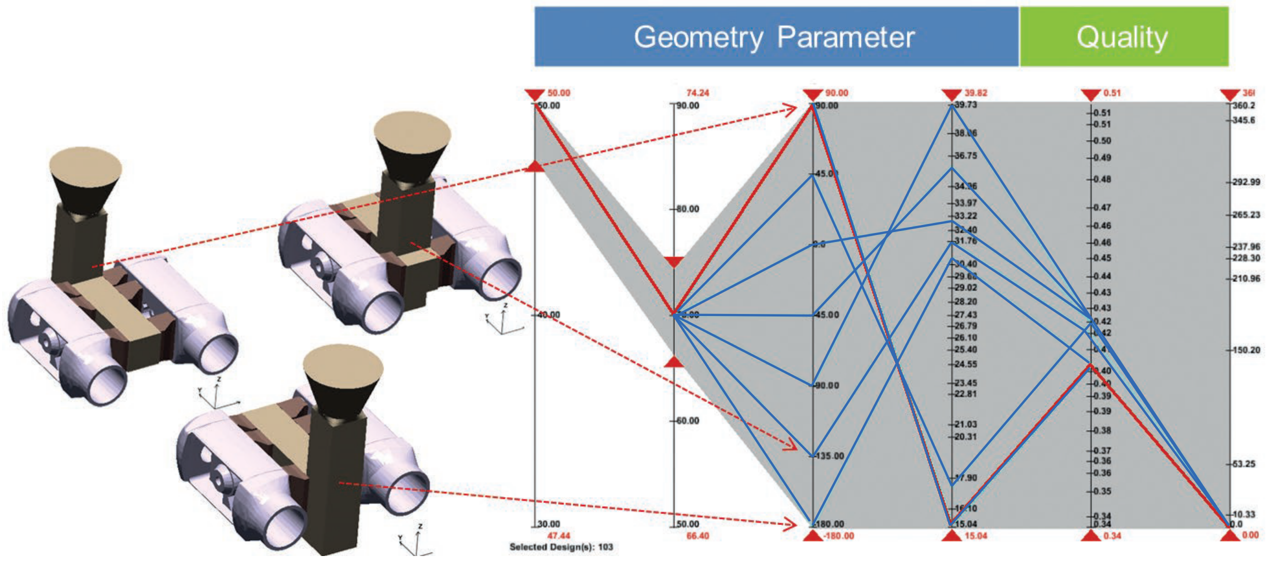

Figure 18: Evaluation of the impact of design variables on the selected quality criteria using a parallel coordinate diagram. Each blue string of lines displays the set of variables and resulting quality of one virtual experiment.

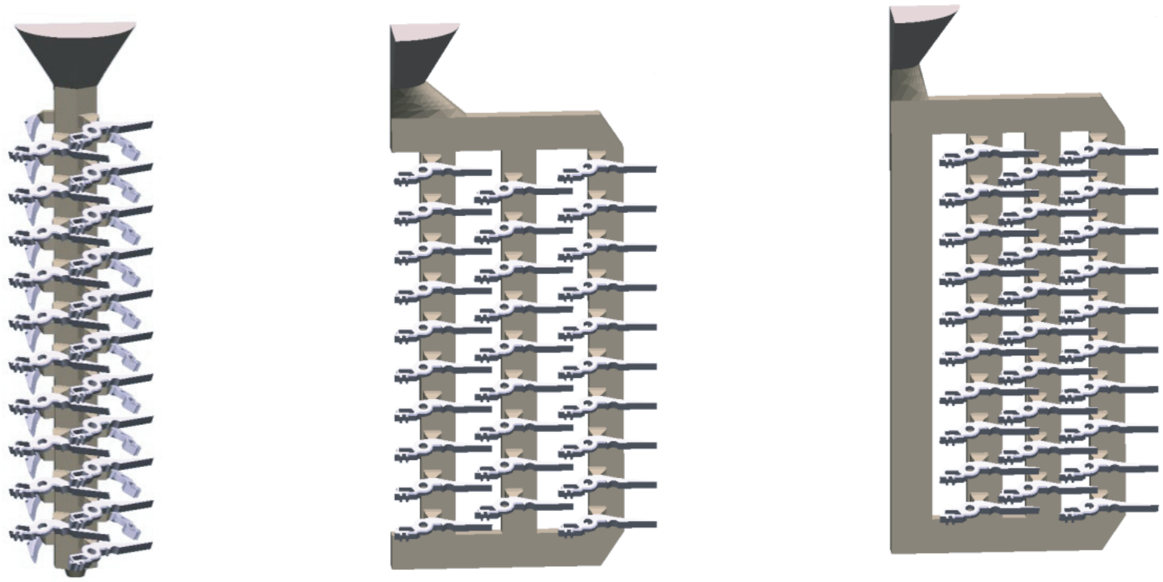

Figure 19: Investigation of re-oxidation inclusions for different gating designs [7].

the objective is to minimize turbulence and gas entrapment during filling and guarantee sufficient feeding during solidification. These objectives are often compromised by the need to design the tree to stand the manipulation and mechanical loads during coating and sanding. For many steel castings, re-oxidation inclusions are a major cause for rework or even scrap. The formation of inclusions is closely linked to the turbulence during filling. Using flow turbulence simulation during filling, the resulting gas entrainment and the probability and size of inclusions can be modelled quantitatively (**Figure 19**). In this case, different gating concepts were investigated with respect to their sensitivity creating re-oxidation inclusions in the casting. **Figure 20** illustrates the predicted distribution and amounts of inclusions for casting located at the top and the bottom of the tree. A clear difference in predicted inclusions between the three different tree designs as well as between top and bottom parts can be seen.

5.2.3. Searching for the best way

Many precious metal parts are investment castings. Therefore, it is one of the greatest challenges for jewelry manufacturers to find a good balance between casting quality and cost effi-

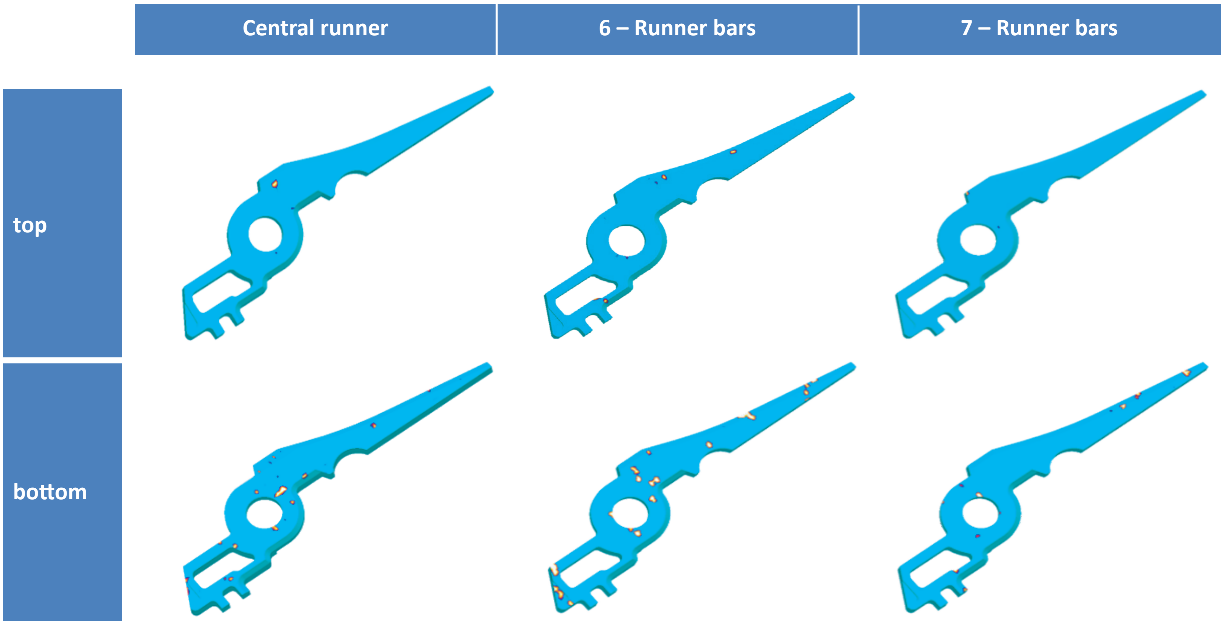

Figure 20: Impact of the gating design on the number and distribution of re-oxidation inclusions on the surface of a casting [7].

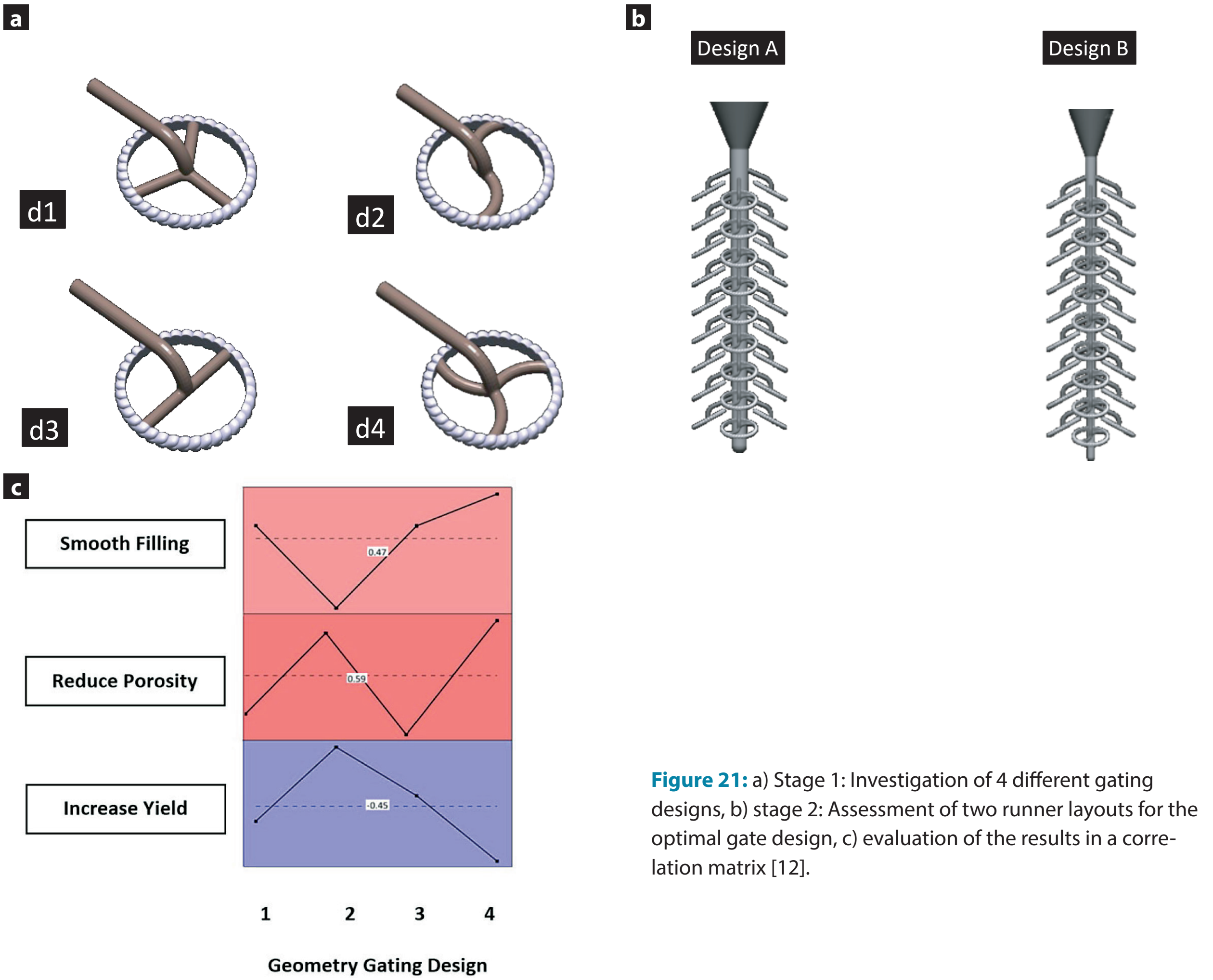

Figure 21: a) Stage 1: Investigation of 4 different gating designs, b) stage 2: Assessment of two runner layouts for the optimal gate design, c) evaluation of the results in a correlation matrix [12].

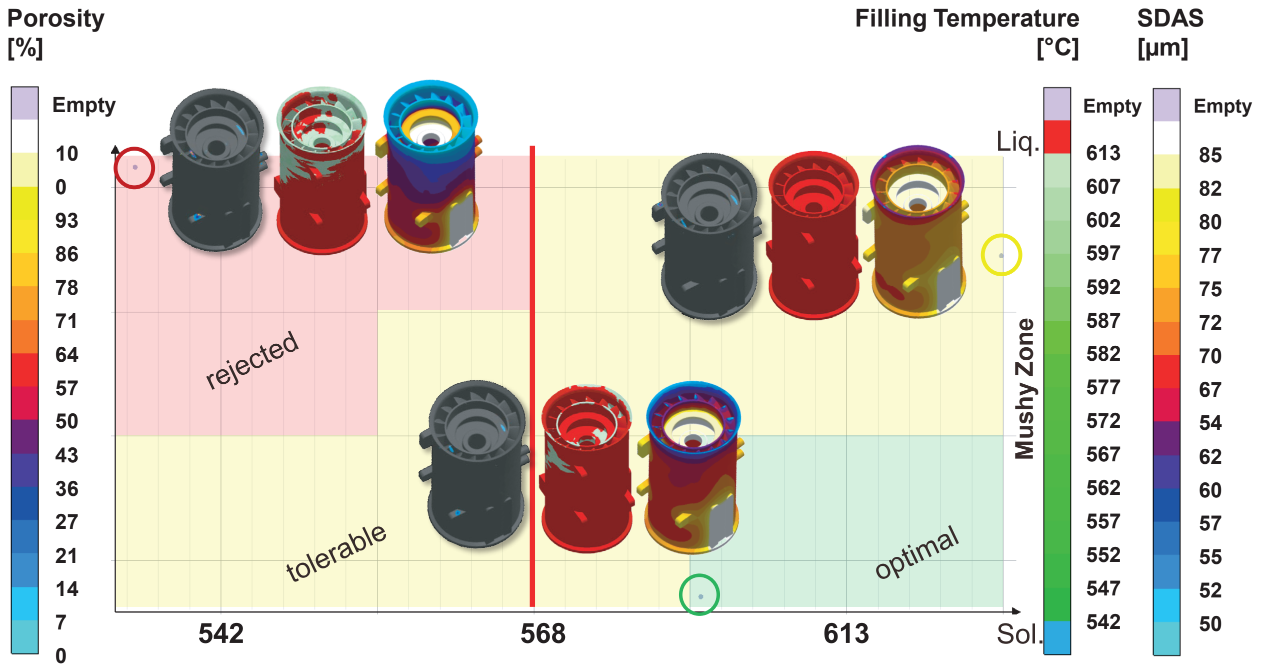

Figure 22: Quality chart (here porosity level vs. misrun tendency for different shell preheating temperatures) to establish optimal operating conditions and robust part quality [7].

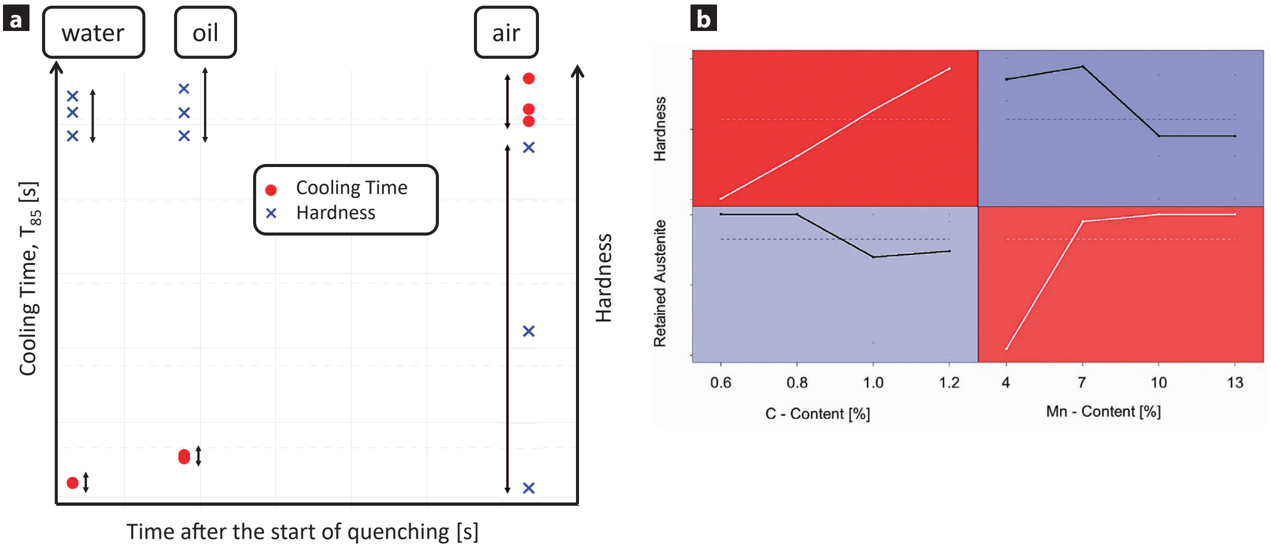

Figure 23: a) Impact of the cooling medium on the cooling time as well as on resulting hardness; b) main effect diagram showing the effect of alloying elements (C and Mn) on the microstructure (retained austenite) and resulting material properties (hardness) after heat treatment.

ciency. **Figure 21** illustrates the possibility of providing comprehensive solutions on process optimization for investment casting in the jewelry industry using the example of a ring. The ring should be made of the silver alloy AgCu7. A 2-stage design selection process was done with the objective to find the best gating of the individual ring casting in stage 1 (d1 to d4). Stage 2 was used to further optimize the assembly setup (design A and B) [12].

To measure the outcome, two different quality criteria (smooth filling and porosity) were investigated and compared to the respective yield. The correlation matrix (Figure 21) reveals that design d2 shows the best compromise between smooth filling (less turbulence or splashing during filling) while still achieving the highest yield among all other designs. In stage 2 two possible tree designs with different runner diameters were chosen using the selected gating design (d2). Subsequently, another virtual DoE was conducted for the two tree designs with one additional objective to avoid or minimize misrun. The evaluation of the two designs for all criteria clearly indicated that design B was the better choice, because of lower turbulence during filling as well as lower porosity, higher yield and minimal tendency for misruns.

5.3 Linking technology decisions with robust quality and optimized cost

Investment casting foundries are always aiming to establish a process window that guarantees robust quality according to specification and optimized costs over the entire casting process. Knowing the impact of technical decisions on resulting costs due to repair or even scrap is a key to make reliable decisions. This simplified case study of an air flow housing demonstrates how changing a process parameter (preheating temperature of the shell mold) affects the casting quality (risk of misruns, shrinkage porosity and microstructure (Dendritic Arm Spacing)), (**Figure 22**). The aluminum structural casting (A356) has a weight of 64 kg and a height of 90 cm. The simulations were performed for three different shell preheating temperatures (200 °C, 400 °C and 600 °C). The main objective was to find the best compromise between minimum porosity amounts and minimal risk for misrun for an acceptable DAS level. The shell preheating temperature has a considerable influence to avoid misrun. As the shell temperature is reduced, the risk for misrun in the casting obviously increases, whereas the DAS level is lowered. On the other hand, the amount of porosity increases as well at low as at high preheating temperatures and has a minimum at 400 °C. The systematic evaluation of the given process window enables the assessment of casting quality and cost impact as well as the robustness or safety margin of the nominal operating point at the same time.

5.4 Robust and optimized heat treatment process conditions

A robust industrial process for high quality investment casting products requires the consequent reduction of process fluctuations on the part quality after heat treatment as well as robust and optimized process conditions. Autonomous Engineering allows assessing the influence of heat treatment process variables on the resulting microstructure and mechanical properties by performing Design of Experiments virtually. The objectives of the optimization are to realize the best compromise between the microstructure and material properties as well as to use resources efficiently, e. g. energy, treatment time and production capacity. All significant process variables such as the thermal history and the chemical composition of the alloy on resulting part quality can be investigated systematically.

Figure 23 shows the results of a virtual DoE investigating the effect of different cooling media during quenching of a steel casting on the cooling time as well as on the resulting hardness. The hardness scatter in the casting is strongly dependent on the cooling medium. The figure also shows how the chemical composition, in this example carbon and manganese, affect the microstructure (retained austenite) and the resulting material properties (hardness) after heat treatment. The example demonstrates how systematic virtual experiments provide quantitative insights to establish optimized process conditions.

6 Conclusions

Having started in the early days mainly to produce artwork, investment casting has developed over the years into a reliable manufacturing process serving various industries with high-integrity castings. Current challenges the process is facing, such as substitution threats by additive manufacturing, globalization and related price competition, as well as the inherent process and production needs make it vital to use simulation tools to support design and process related decisions. The systematic use of virtual experimentation and optimization changes the simulation methodology from a confirmative tool of already taken decisions to a predictive tool allowing the investment caster to set up optimal operating points and robust process windows for the entire manufacturing route before the first casting is made.

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