Robust castings and processes in high pressure diecasting through virtual process analysis


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Meeting Manufacturing Requirements

- **Fast** Product and Process Development
  Minimal development time for casting design, gating layout and tooling

- **Optimized** Products and Processes
  Quality, casting yield/expenses
  What's the optimum operating point?

- **Robust** Process
  Keeping parameter variations low – Reproducibility!
  How accurately do I have to hold the operating point?
What means „simulation“?

- Simulation means to emulate or copy a dynamic process in a system with the help of an experimental-capable model to gain knowledge which is transferable to reality. [VDI-Richtlinie 3633]

- In clear words
  - create a virtual model based on your reality,
  - experiment with this model
  - draw conclusions and gain knowledge for your reality
From „Simulation to Optimization“
Automatic Virtual Experiments

Initial State

Optimization

Best Compromise

Virtual Optimization

1-dimensional Optimization (manually)

Process variables / Degrees of freedom / Start sequence

Automatic modification of lay-out / process variables

Automatic simulation of virtual experiments

Automatic analysis and assessment of measurable quality criteria

Automatic

Targets

Profitability

Quality

Systematic Virtual Experiments (DoE)
Analyze your product and process systematically

MAGMA\textsuperscript{5} methodology to see what happens – before it happens!
Development of a Sports Car Structural Part

First Concept

Packaging and Module Analysis

First Design of Structural Casting

Castable Design

Functional Designing

Producible Design for HPDC
Functional Areas and Specifications

Specification of critical functional areas

Connection types
- Self-piercing rivet
- Monobolts
- Flow drilling screws
- Structural Adhesives

Simulation of Crash according to FMVSS
- Load-test acc. FMVSS Norm (frontal)
  - 56 km/h
  - 100% Overlap
- Design Concept is capable to transfer crash loads to the middle tunnel.
Feasibility Study - HPDC

Development of Gating System

Basic Analysis → Ingate Layout → Final Design

Simulation of Filling and Solidification of target-process verifies feasibility of the structural casting
Knowledge is lost!
Many simulations stay as single results

Working in version 12, what do you still know about the results of version 2?
Track all Targets through the Development Process

<table>
<thead>
<tr>
<th>Version</th>
<th>Fill Pattern of Part</th>
<th>Porosity of Part</th>
<th>Porosity lower Connections</th>
<th>Porosity upper Connections</th>
<th>Risk of ColdFlow upper Rip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Ingate Layout</td>
<td>204241168.0</td>
<td>3.05</td>
<td>0.87</td>
<td>3.69e-07</td>
<td>656.35</td>
</tr>
<tr>
<td>Ingate Variation</td>
<td>233107264.0</td>
<td>3.27</td>
<td>0.94</td>
<td>3.90e-07</td>
<td>642.32</td>
</tr>
<tr>
<td>Gating w/o Overflows</td>
<td>199002208.0</td>
<td>5.54</td>
<td>0.79</td>
<td>4.72e-06</td>
<td>619.83</td>
</tr>
<tr>
<td>Final Casting Layout</td>
<td>15245536.0</td>
<td>2.12</td>
<td>0.72</td>
<td>5.28e-06</td>
<td>618.65</td>
</tr>
</tbody>
</table>

- **Level of Porosity in lower Connection Point**
  - low
  - smooth
  - turbulent

- **Risk of Coldflow in upper Rip**
  - higher
  - lower

- **Material Quality of upper Connection Points**
  - higher
  - lower
Simulation of residual stresses and distortion

Von Mises Stresses and Distortion after trimming

Area of high local residual stresses

Potential Failure of Casting in case of overlapping loads during crash

Effective Plastic Strain resulting from casting process

Critical irreversible pre-damage of Microstructure caused by high plastic strain

Risk of local reduced mechanical properties of casting
Reasons to do autonomous Optimization?

„Improve the solution“

There is always a better solution!

Start design
Manually optimized
Optimum Designs
Minimize velocity at the gate

Smooth filling of Casting
Simple evaluation of effects
DoE on Die-Open-Time

Process: Influence of Die-Open-Time on distortion and stresses in critical areas

Variable: Die Open Time (9.3s, 14.3s, 19.3s, 24.3s)

Quality Criteria: Max. Displacement in X and Max. vonMises

Objective: Evaluate optimum Die-Open-Time to minimize distortion and stresses

Main Effects of Die-Open-Time Variation on Distortion and Stresses
Visual Assessment of Experiments

Die Open at 9.3s

Die Open at 24.3s
Validation of FE-Crash-Analysis

Favourable **Overlap** of compression stresses during crash and **residual tensile stresses** from casting process.

High von Mises stresses form casting process with majorly tensile stresses after ejection and cooling of casting.
Why should I use virtual DoE’s?
Especially already during the early development phase

Do you always know the position of your own „optimum“ solution?

Quality

Stable Optimum

Your optimum operating point

At the edge of the process window

Instable Optimum

Process
Nominal Casting Design and Process Layout

Simulation model with Evaluation Areas of several specified requirements

Area 2 “Thin Wall”

Area 1 “Connecting Points”

Setup initial Process Conditions

Typical shot profile for HPDC Castings based on piston travel/velocity plot

Deceleration of shot piston at end of filling to avoid flashing

Nominal Casting Design and Process Layout

Typical shot profile for HPDC Castings based on piston travel/velocity plot

Deceleration of shot piston at end of filling to avoid flashing
Preparing the Virtual Process Analysis (DoE)
Investigate a broad variety of variables and targets

Design Variables

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Lower Limit (mm)</th>
<th>Upper Limit (mm)</th>
<th>Step (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry hpd_c_inlet_001 - Biscuit thickness ( h )</td>
<td>15.0</td>
<td>30.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Design Variable</td>
<td>Lower Limit (°C)</td>
<td>Upper Limit (°C)</td>
<td>Step (°C)</td>
</tr>
<tr>
<td>Cast Alloy Class - Initial Temperature</td>
<td>620.0</td>
<td>650.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Design Variable</td>
<td>Lower Limit (bar)</td>
<td>Upper Limit (bar)</td>
<td>Step (bar)</td>
</tr>
<tr>
<td>Intensification - Working Pressure ( [p/w] )</td>
<td>20.0</td>
<td>820.0</td>
<td>800.0</td>
</tr>
</tbody>
</table>

Dosing Tolerance & Initial Melt Temperature

Intensity of Spot Cooling

Spraying Conditions

Intensification

Temperature Drop Estimation
- Oven temperature: 792.39 °C
- Initial temperature (estimated melt temperature in chamber): 660.0 °C

MAGMA
Impact of Dosing Variation
Manageable Information – Main Effects

What happens with dosing variances?

- **Minimal Dosing**
  - Start of Deceleration “Breaking”
  - 15

- **Nominal Dosing**
  - Start of Acceleration “2nd Phase Velocity”
  - 22.5

- **Maximal Dosing**
  - 30

**Main Effects of Dosing Variance on Filling Time**

<table>
<thead>
<tr>
<th>Dosing Level</th>
<th>Filltime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (15)</td>
<td>35</td>
</tr>
<tr>
<td>Nominal (22.5)</td>
<td>31</td>
</tr>
<tr>
<td>High (30)</td>
<td>27</td>
</tr>
</tbody>
</table>

7ms difference in filltime within the casting – corresponds to 25% variance on total filltime of 30ms.
Expert Knowledge virtually generated
Correlation Matrix – Tendencies and Dependencies at a Glance

Analyze the Influence and Dependencies of all Process Variables for every available MAGMA® result without additional simulations.
Focus on the critical parameters before the first part is produced.

From Specification...

Quality Criteria:
- Area 2 Misrun Thin Wall
- Smooth Filling of Runner/Gating
- Smooth Filling of Casting
- Area 1 Porosity Connecting Points
- Max. Difference of Filltime in Casting
- Average Filltime of Casting

Process Variables:
- Dosing Variance
- Intensification Pressure
- Initial Melt Temperature
- Intensity of Spot Cooling Area 2

...to robust ramp-up and production.
**Optimize** your process in one heat

See the big picture with MAGMA\(^5\) methodology - taking the whole manufacturing process into account
Heat treatment of a Structural Component

Heat Treatment Process has two main target:
- Realizing the required Mechanical Properties
- Tune in Dimensional Tolerances according specification

Current process layout and rack design is based on experience and extensive experimentation.
Initial simulation model for support frame was based on the contact areas detected in previous real experiments.

A comprehensive simulation model considering strain rate sensitivity and creep at elevated temperatures was applied.
Virtual Experimental Heat Treatment Trials
Automatic evaluation of different temperatures and holding times

**Process:** Solution treatment for 2 hours at 485 °C

**Variable:** Holding Temperature (465°C, 485°C, 535°C) and Holding Time (1500-7800s)

**Quality Criteria:** Max. Displacement in gravity direction (Y)

**Objective:** Minimize Distortion (Y) of Casting after Heat Treatment

This allows a quantitative prediction of distortion before the first real physical experiment has been performed.
Virtual Experimental Heat Treatment Trials
Automatic preparation and simulation of different support frame layouts

**Process:** Solution treatment for 2 hours at 485 °C

**Variable:** Geometry exchange of different support struts

**Quality Criteria:** Max. Displacement in gravity direction (Y)

**Objective:** Minimize Distortion (Y) of Casting after Heat Treatment

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**Initial Layout**

Sidewise stabilising beam

**Version 01**
without small strut

**Version 02**
without large strut

**Version 03**
moved small strut
Identifying the best support frame layout

- **Initial Layout**
- **Version 01 without small strut**
- **Version 02 without large strut**
- **Version 03 moved small strut**

Displacement $Y$ mm

Gravity

Versions 01 and 03 are marked as acceptable.
Casting Process Simulation with MAGMA\textsuperscript{5}…

- …is a \textit{Virtual Test Field} with high degrees of freedom without economic or production risks
- …supports the search for the \textit{Optimal Operating Point} in terms of measureable quality, yield and cost
- … enables the automatic evaluation of a \textit{Process Window} by fast and easy assessment of process alternatives
- …assists in establishing \textit{Reproducible Processes} and understanding how process variability affects casting quality
- …generates \textit{Systematic Knowledge} on correlations between manufacturing parameters and quality criteria of the cast part
- …empowers „Frontloading“ through secured early stage decision making for \textit{Robust Product and Process} development