Many components of high pressure die casting call for the use of undercuts and channels for conducting various media. Nowadays, these components cannot be manufactured from a single casting. However, for certain component shapes, the lost core process offers an interesting solution. The process involves inserting salt cores before aluminum die casting and rinsing them out with water under high pressure. Bühler is currently waiving all of its patent rights to this process and is making all of its pertinent technology know-how available on the market. This includes patent families EP 2 022 577 A1, EP 2 277 644 A1 and EP 2 425 910 A1 with protective rights in Europe, Japan and the USA. The technological and economic basics of the process are outlined below.

The lost core process makes it possible to develop completely new components and make internal designs significantly more complex. However, there are many other factors to be considered when using salt cores. Basically, the strength of the salt cores is largely influenced by the salt mixture used. The research department at Bühler tested and compared the bending strength of various salt mixtures. This work was based on the tests performed by Tohoku University and Yamaha 2007 [2]. The highest degree of bending strength was achieved with a weight ratio of 38% KCl to 62% Na₂CO₃.

As a rule, the bending strength of a given salt mixture is at its lowest at the eutectic composition or when it is considered individually at its pure components. The highest degree of strength is reached as the intermediary composition between the eutectic and the pure component.
The primary particles perform a deflection function in the event of any cracking.

The bending strength was determined and calculated by using test specimens during a 3-point bending test.

$$\sigma_b = \frac{3 \times F_{\text{max}} \times L}{2bh^2}$$

The bending strength was determined using the 3-point bending test.

The bending strength exhibits a high degree of variation between 23 MPa and 39 MPa.

For the salt core’s strength calculation we apply 23 MPa as bending strength.

This characteristic however, is typical for salt cores and comparable to the characteristic of ceramic materials. Other compositions of salt mixtures also demonstrate a high level of strength variation. In addition to bending strength, additional physical properties of the salt composition used must also be taken into consideration.

<table>
<thead>
<tr>
<th>Material property</th>
<th>Solid</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcool temperature [°C]</td>
<td>-</td>
<td>500</td>
</tr>
<tr>
<td>Liquidus temperature [°C]</td>
<td>-</td>
<td>640</td>
</tr>
<tr>
<td>Density [kg/dm^3]</td>
<td>2.33</td>
<td>1.15</td>
</tr>
<tr>
<td>Specific heat [kJ/kg/K]</td>
<td>1.6 - 1.7</td>
<td>1.6 - 1.7</td>
</tr>
<tr>
<td>Thermal conductivity [W/m·K]</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Specific latent heat of fusion [kJ/kg]</td>
<td>-</td>
<td>7200</td>
</tr>
<tr>
<td>Thermal expansion coefficient [K^-1]</td>
<td>25-36 at 8-190°C</td>
<td>23-46 at 8-170°C</td>
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<tr>
<td>Viscosity [mPa·s]</td>
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<td>10000</td>
</tr>
<tr>
<td>Young’s modulus [kN/mm²]</td>
<td>&gt;10000</td>
<td>-</td>
</tr>
<tr>
<td>Friction min [ ]</td>
<td>0.18 - 0.24</td>
<td>-</td>
</tr>
<tr>
<td>Bending strength [MPa]</td>
<td>23-39</td>
<td>-</td>
</tr>
<tr>
<td>Solidification shrinkage [%]</td>
<td>18.6</td>
<td>-</td>
</tr>
<tr>
<td>Solid shrinkage [%]</td>
<td>1.5 - 2.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Physical properties of the salt mixture KCl (38%) / Na₂CO₃ (62%) [2].

The liquidus temperature, density and thermal conductivity are significant for salt core production process. The liquidus temperature of the salt mixture used corresponds approximately to the temperature of aluminum during the filling phase. Since the filling phase of the aluminum die casting process takes only a few milliseconds and the aluminum solidifies very quickly due to its high level of thermal conductivity, the salt core does not melt while it is recast with aluminum. With regards to density, we must take into account the greatest difference between solid and liquid states. The volume of the salt core is reduced by around 18.5 percent during solidification. Last, but not least, the low level of thermal conductivity slows down solidification during the pressure intensification phase, thus increasing the cycle time.

Producing Salt Cores

The process for producing salt cores is similar to the aluminum die casting process. The salt is melted in a crucible furnace. The metered amount is ladled directly into the shot sleeve and then pressed into the die with the plunger. Nevertheless, a few differences must be considered: a thicker gate, higher die temperature, lower filling speed, a longer pressure intensification phase and subsequent thermal treatment. The gate must be made thicker than typical aluminum casting gates in order to prevent the gate from closing too soon, since salt solidifies very quickly.
Having a thicker gate makes it possible to intensify the pressure for a longer period of time and to compensate somewhat for the shrinkage of 18.5 percent due to solidification.

Having a higher die temperature reduces the effect of surface solidification which would make it more difficult to completely fill the cavity around the thinner areas of the core. Tensile stress and defects on the surface of the salt core can be reduced by increasing the temperature of the die – as has been demonstrated by tests conducted by Yamaha [3]. Filling at a lower speed prevents the molten salt from spraying beyond the die due to its lower viscosity. As a rule, since the thermal conductivity of the salt is lower than that of liquid aluminum, the pressure intensification phase has to be increased. For salt cores that are susceptible to cracking, a subsequent heat treatment is required. This mainly affects thicker salt cores since the high temperature gradient through the thickness leads to thermal stress. The thermal treatment lasts an hour at 250°C.

Infrastructure

Producing aluminum components using lost core technology requires an expansion of existing infrastructure.

The two salt components are coarsely blended in the mixer by means of a screw conveyor and then fed into a melting furnace with a ceramic crucible. The ceramic material must be resistant to molten salt and thermal shock. The mixture is fused in the furnace and then fed into the shot sleeve with a ladling device made of Inconel 600 and a wall thickness of max. 1 mm. This material is resistant to molten salt and high temperatures. The ladle is completely submersed during the waiting period to ensure that any adhering salt is melted. The salt core is then cast using a standard die casting machine and, depending on the complexity of the salt core geometry, it will subsequently undergo a quality inspection. Since the salt cores absorb moisture from the ambient air quickly, they have to be vacuum packed in sealed edge aluminum pouches.

The aluminum die casting is the next step. Particular attention must be paid to ensure that the pressure intensification phase only begins once the salt core has been completely recast. A high degree of reproducibility of the filling phase is crucial to that goal. It can only be achieved by using a real-time controlled die casting machine. Also unnecessary stress placed on the salt core due to an over-loaded bearing must be avoided.

After the aluminum casting, the salt cores are rinsed out of the component with high pressure water. The cycle time for the core removal process is usually long, so the core removal tool must be designed to be able to process multiple components at the same time. The salt material removed from the core can be recycled, but that is a time-consuming and expensive solution, which makes environmentally-friendly disposal more economical. Waste water, however, is usually returned and reused to remove additional cores.

A control container to measure the salt content ensures that the content of the salt does not exceed around 100 g per liter. The core removal process and waste water treatment are expensive and cost about the same as salt core production. This must be considered in the business plan.

Simulations

If a component is manufactured through the lost core process, simulations are indispensable.
The filling process is simulated for producing salt cores as well as for die casting the aluminum. Simulation studies are used to optimize the gate design and the venting system. When salt cores are being produced, entrapped air may cause cracks in the casting. Filling simulations are used to compare various filling profiles to minimize or eliminate entrapped air. Simulating the solidification process allows us to determine areas where shrink porosity might appear as the salt solidifies.

The fluid structure interaction simulation (FSI) is basically used to calculate the impact of the forces of the molten aluminum on the core.

However, since various factors such as e.g. core bearing and calculating how much heat is transferred to the salt core are very difficult to simulate, its significance is limited. Another short-coming of the FSI simulation is the lack of temperature-dependent mechanical properties of the salt core. Furthermore, salt cores are inhomogeneous because the micropores from solidification are distributed irregularly throughout. These short-comings limit the quantitative significance of the FSI simulation.

**Design Guidelines for Salt Cores**

For the practical application of the lost core process there are various aspects to be considered:

- **Compared to aluminum die casting**, the solid shrinkage is greater and dependent on the geometry of the salt cores. For thin-walled salt cores (5–7 mm), the shrinkage is approx. 1.3–1.5 percent. For greater wall thicknesses, shrinkage increases up to 2–2.2 percent.

- **Salt cores must be able to shrink freely within the die**. A U-shaped salt core could cause cracks. This is counteracted by the enlarged draft angles and the generous rounding off of the inside edges.

- **Annular geometries as e.g. a water jacket, requires at least a 2 degree draft angle on the inside.**

- **The salt core may not remain loose within the die**. It is slightly clamped by small grooves at the core pin. Slight dimensional deviations due to the shrinkage of the molten salt, can be compensated.

In the best case scenario, a core bearing only defines the horizontal position and a second bearing position defines the vertical displacement. As a rule, the salt core must be able to expand as it absorbs heat without causing pressure marks. The location of the bearings should also prevent the core from rotating while it is recast with aluminum. No other additional positioning may be done. Nevertheless, support points have proven to be very helpful for long salt cores. They have to be free-standing when they are inserted and may not cause any stress when the die is closed.

- **Since salt cores usually only represent a small part of the component**, the volume is rather small and the degree of filling in the shot sleeve is relatively low. By using a multiple cavity, the degree of filling can be increased. This measure reduces the loss of heat of the molten salt and minimizes pre-solidification of the salt. The slow filling process also generates early solidification at the inner surface of the shot sleeve. If this solidified salt enters the cavity, cracks will appear. That is why the gate system must be high volume as compared with the salt core’s cavity.

The area of the gate must be designed just like for a squeeze part to ensure that a component is completely filled at the lowest speed possible and then pressed (3rd phase) for a long time.
It makes sense for the rest of the process to place the gate to a bearing position so that the gate system can be separated by fracturing. Punching is not possible for the salt process.

– The slow filling velocity makes it possible to keep the venting cross-section small for producing salt cores. For venting using a chill-block, we recommend have a gap of 0.3 mm, since the molten salt could squirt out if the gap is any bigger.

Physical Limitations of the Process

The lost core process produces salt cores with high mechanical strength while maintaining freedom of design. However, this is also subject to limitations. The salt mixture used exhibits a high solidification rate (approx. 18.5%) that negatively affects the dimensional accuracy of larger salt cores. The deviation from the target geometry may be up to ± 0.3%. This substantial geometric deviation might make inserting salt cores more difficult, since any oversizing will cause high stresses on the salt core print areas. Because of the added stress and its brittle characteristic, the salt core could break even before it is recast with aluminum. Finally, the low degree of thermal conductivity extends the pressure intensification phase as well as the cycle time, making manufacturing thick salt cores (>20mm) more expensive.

Assessing Technical Feasibility

Since lost core technology is only feasible for certain geometries, the first step is to assess its technical feasibility. The following requirements must be considered during an initial, rough assessment:

– Is the salt core thicker than 6 mm on all areas?
– Can the salt core be removed from the die? The draft angle should be at least 2 degrees.
– Is the thickness ratio between adjacent subsections of the salt core > 0.7? (Refer to point A)
– The salt core should be designed without sharp changes of flow-direction which would result in a high degree of shrinkage in the die.
– Is it possible to design the salt core to ensure that all notch radii are greater than 5mm?
– The bearing in the aluminum die may not be over-loaded.
– The de-coring process may not be forgotten. Is the geometry suitable for the de-coring process? Are there any cross-sections, recesses or diversions that would negatively affect this process?

Furthermore, the caster must have the appropriate freedom of design in order to modify the component’s design if necessary.

Economic Profitability

These days, components with undercuts and complex channels are often cast by means of gravity die casting using sand cores. This process is well-established; however, for large components that only require a small core, it is expensive. This is where the lost core die casting process would be considered an attractive alternative.

The manufacturing costs of the salt cores are calculated primarily from raw material costs and cycle time. The salt mixture consisting of 38% KCl and 62% Na2CO3 costs about 0.35-0.4 Euro per kg (for ordered amounts exceeding 20 tons). The cycle time depends on the component; as a rule it is longer than for aluminum casting. Since the molten salt transfers heat to steel very slowly, the pressure intensification phase is extended. The solidification time of the salt can be double that of aluminum.

Any economic assessment must also take into account the huge investment costs for core removal and water treatment infrastructure.
Conclusion

The opportunities offered by the lost core process are interesting; however, they are also subject to technical and economic limitations. In order to use the lost core process profitably, technical feasibility and manufacturing costs must first be carefully considered. This requires comprehensive basic knowledge and in-depth process know-how. For a first feasibility check Bühler is happy to make its knowledge and expertise available in order for users to further develop the process independently.

Bibliography:

