Choosing a durable tap-hole design is one of the most important tasks in the refractory lining engineering process for a furnace, as a reliable and safe operation depends on the tap-hole performance. The evolution of tap-hole designs is very often a result of a trial-and-error process that relies on experience and know-how gathered over many years of furnace operation. Designing tap-holes always requires a comprehensive consideration of the problems involved, e.g., the refractory design cannot be done independently from the cooling design, and the cooling and refractory design must cater for a smooth and safe tapping procedure but also allow easy maintenance work. The tap-hole area is exposed to high thermal and mechanical loads. Thermal shocks, erosion due to the fluid flow around and through the tapping channel, opening and closing practices, and chemical corrosion all contribute to tap-hole wear. A predominant cause of wear is difficult to identify as tap-hole designs, as well as operational boundaries and parameters of nonferrous and ferroalloys smelters, are highly diversified, which complicates comparison and analysis. Numerical simulations are essential for design improvements and changes since they allow a systematically prediction of the influence of different design parameters. A thermomechanical simulation case study is discussed which assesses the influence of different tap-hole block designs on the evolving stresses. The study was conducted with commercial finite element software. The results indicate that increasing the size of rectangular-shaped tap-blocks or changing to cylindrical ones might be advantageous. Furthermore, differences between a flexible and a stiff refractory surrounding the tap-block can be detected. Cooling is shown to have a detrimental effect since it increases the thermomechanical stresses in the tap-block.

Keywords: simulation, tap-hole, design, thermo-mechanical, stresses.

INTRODUCTION

A well-performing tap-hole is probably the most essential requirement for a smooth and trouble-free smelter operation. From a refractory point of view it seems odd to build a hole into a structure whose main purpose is to keep liquid metal and slag in a defined process environment to ensure the integrity of a furnace. Inevitably, metal and slag must be removed from the process in a controlled and safe manner, and therefore a tap-hole is a necessity. In an ideal case, the tap-hole longevity would equal the service life of the smelter refractory lining. However, the tap-hole area is exposed to extreme thermal and mechanical loads. A combination of thermomechanical loads, erosion due to the fluid flow through the tapping channel and around the tapping channel inlet, opening and closing practices, and chemical corrosion contribute to tap-hole wear.

A predominant wear cause is difficult to identify as the nonferrous and ferroalloys industries use a variety of tap-hole configurations, designs, and tapping procedures, which makes comparison difficult. Depending on the considered metal or matte and the post-processing route, a furnace might have one or two tap-holes for tapping of slag and metal through the same tap-hole (e.g., top submerged lance furnaces), multiple single-phase tap-holes (e.g., two or more metal/matte and slag tap-holes (common for circular EAFs, six-in-line furnaces, and flash smelting furnaces) for tapping slag and metal separately, a bottom tap-hole with a slide gate (more common for EAFs in the steel industry), no tap-hole for tilting operations (Peirce-
Smith converter), or a siphon (e.g. QSL reactor or Vanyukov furnace). The tap-holes might be equipped with different kinds of cooler designs with different cooling intensities. Operational practices can be divided into batch or continuous tapping, the tap-holes could be opened by drilling, lancing, or a combination of both, and closure might be done with a mud gun, manually, or by a slide gate. Finally, the choice of the refractory quality, the clay type used, and the maintenance practice will influence the overall service life. (Nelson, 2014)

More studies of the type conducted by Nolet (2014) for all kind of smelters and diverse metals, mattes and slags would be necessary for better identification of tap-hole wear mechanisms and to set up realistic benchmarks for tap-hole service life. Most tap-hole designs are a result of a trial-and-error development over many years of operational experience. The factors with most influence on the wear of a specific tap-hole are most likely not known, which makes it difficult to recommend improvements for future designs. Thus, numerical simulation plays a key role in developing and improving tap-hole refractory designs. Even so, it is not feasible in practice to integrate all physical phenomena taking place during tapping into one model (Kreuzer et al., 2018). Simulation is needed to find answers for certain problems, such as identification of peak thermomechanical stresses in the refractory bricks during tapping using finite element analysis or evaluating thermal profiles of tap-hole cooling systems and their influence with CFD software.

The following sections show how numerical simulation can be used to clarify the impact of cooling, and size and shape of the refractory, on the evolving mechanical stresses in tap-blocks.

**A THERMOMECHANICAL APPROACH TO TAP-HOLE REFRACTORY DESIGN**

**Objective**

One very common phenomenon is the evolution of cracks in the tap-hole refractory during tapping, as shown in Figure 1. These cracks are caused by thermo-mechanical stresses that evolve due to the unsteady-state temperature fields in the tap-hole area. Figure 2 shows the simulated evolution of the temperature in tap-blocks for several tapping cycles. The simulation started from the initial tap with a steady-state temperature field for a closed tap-hole channel. It is evident that several tapping cycles are needed to achieve a constant mean temperature. During tapping and cooling the refractory temperatures cycle around this mean temperature. An increase in temperature leads to thermal expansion and a decrease to contraction of the refractory material. Stresses evolve due to either a restriction of movement during expansion or contraction of the material or unsteady-state temperature fields. The restriction of movement is caused e.g. by the surrounding refractory material, a cooling plate, or the steel shell, which have different expansion coefficients, or if the design of the surrounding refractory, the steel shell, or the coolers results in a rigid structure. An unsteady temperature field that evolves during heating or cooling of refractory material causes internal forces and stresses even without restriction of movement. For instance, a refractory brick has to adapt its shape to a temperature change according to the thermal expansion values. This shape change will be obstructed by the microstructural bonds of the refractory material, leading to internal stresses. Those stresses vanish in a steady state for a simple rectangular brick and their magnitude depends on the heat conduction in the brick and the rate of temperature change. Apart from the right choice of the refractory quality, the shape and the size of refractory bricks are decisive for the evolving stress magnitudes (Bradley, 1985). Furthermore, infiltration of the
bricks will alter their physical properties, and additional mechanical or thermal impacts during opening and closing promote further cracking.

Figure 1. Cracks in a tap-block after several taps.

For a long-lasting tap-hole it is of great importance to know the general relationships between brick dimensions and shapes and the evolving thermomechanical stresses in the refractory material. Therefore, a finite element analysis was conducted on a typical refractory configuration of a ferroalloy metal tap-hole. The refractory brick dimensions, as well as the boundaries, were varied to evaluate their influence on the thermomechanical stresses.

Tap-hole configuration
A typical ferroalloy metal tap-hole design was used for investigating the impacts of the design changes. Horizontal tap-holes, as shown in Figure 3, are the most common in ferroalloys smelters, consisting of several tap-blocks, which might be changed regularly. The tap-blocks are surrounded by bricks and/or a refractory mix in the cooler. The copper cooler extends the tapping channel and builds some kind of doghouse. Furthermore, it establishes a structure facilitating tap-block changes. Inside, a straight arch helps to maintain the integrity of the furnace lining above when the characteristic funnel-building due to wear of the tap-hole channel starts.
Modelling approach and boundaries
A thermomechanical model was created with the software Abaqus/CAE 6.16. The model does not take into consideration any altering of material or influences of the closing and opening procedures. For example, infiltration lancing, drilling, and fume evolution during closing due to volatilization of organic binders in the tap-hole clay or chemical reactions are not modelled. We attempted to isolate the problem to achieve a fundamental understanding of the tap-hole refractory design.

A simple linear elastic material model was employed for the refractory, which usually leads to overestimated stress magnitudes. An accurate determination of the acting stresses and comparison with the maximum admissible stress for assessing the failure potential is therefore not possible. In reality, the mechanical properties of refractory material are nonlinear and temperature-, time load-, and strain-dependent (Jin, Harmuth, and Gruber, 2014; Prietl, 2006; Routschka and Wuthnow, 2008). A commercial material model that is able to consider these phenomena, or even crack propagation, in coarse-grained material is not available. Furthermore, there exists no standard refractory test method that can be used to derive reasonable strength values for such a comparison. Standard test methods usually consider uniaxial loading of a refractory specimen, but there are crucial differences if a refractory material is multi-axially loaded as in a furnace lining (Prietl, 2006). Nevertheless, the linear elastic material model satisfies the needs of a comparative study since the tensile stresses are identified and their magnitudes with different designs can be compared. As tensile stresses in coarse-grained material will lead to failure at crucially lower magnitudes and much faster than compressive stresses, they can be used as assessment criterion.

A representative section of a tap-hole was modelled as shown in Figure 4a. The cooler, the tap-blocks, and the surrounding refractory were modelled in detail considering one quarter of the tap-blocks. The refractory lining inside the furnace was replaced by a monolithic block for further simplification to reduce computational expenses. The mechanical boundary outside
the tap-hole was realized with a rigid plane (Figure 4b), which could exhibit similar behaviour to a faceplate. A small pressure was applied on the opposite side to avoid horizontal slipping of the tap-blocks. Between the refractory bricks, friction was modelled by employing a friction coefficient.

The copper cooler has inner dimensions of 500 mm × 500 mm, which was retained for the analysis. The following geometrical changes were investigated: a bigger tap-block cross-section of 400 mm × 400 mm instead of 260 mm × 260 mm, the use of larger tap-block bricks without cooling, and doubling the number of tap-blocks by decreasing the thickness, shown in Figure 5. It was assumed that the tap-blocks are surrounded by a refractory mix and bricks. The mix has a very low stiffness, which allows a fairly free movement of the tap-blocks during thermal expansion. Furthermore, the effects of the use of round tap-block shapes surrounded by a well block (shown in Figure 6) and increasing the diameter of the tap-hole channel uniformly, to simulate wear of the channel, were investigated. The refractory tap-hole area was considered as a carbon-impregnated MgO lining. Representative material properties are given in Table I.

The thermal boundaries outside the furnace considered natural convection on the furnace shell with a fixed heat transfer coefficient of 10 W/m²K and an emissivity of 0.7 for surface radiation. The cooling channel was set to a mean water temperature of 45°C. The hot face boundaries were specified at 1500°C. A tapping sequence was established with a tapping time of 20 minutes and a resting time of over 2 hours. For the tapping sequence the tapping channel temperature was set to 1500°C, and during resting the channel surface was considered to be adiabatic. The applicability of the temperature assigned to the tap-hole channel surface is justified in the case of tapping metal with heat transfer coefficients over 1000W/m²K and the general model simplifications. For a slag tap-hole it might be reasonable to employ a heat transfer coefficient, which would damp the temperature on the channel surface and lead to lower stresses in the tap-hole blocks. The chosen boundary represents a kind of worst-case scenario.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>500</th>
<th>750</th>
<th>1000</th>
<th>1200</th>
<th>1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>7.7</td>
<td>5.9</td>
<td>4.6</td>
<td>3.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Specific heat capacity (J/kgK)</td>
<td>1231</td>
<td>1264</td>
<td>1299</td>
<td>1320</td>
<td>1338</td>
</tr>
<tr>
<td>Thermal expansion coefficient 10^5×(1/K)</td>
<td>1.22</td>
<td>1.28</td>
<td>1.36</td>
<td>1.37</td>
<td>1.39</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>3200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Tap-hole baseline geometry, 260 mm × 260 mm tap-block cross-section.

Figure 5. Tap-hole variations investigated.

Figure 6. Cylindrical tap-blocks with 270 mm diameter and surrounding well block.

RESULTS

The maximum principal stress is used for the assessment of the tap-block geometries as it exhibits the highest tensile stress, which will be decisive for the failure of coarse-grained material like refractory. Due to the linear elastic material approach the stress magnitude cannot be used to evaluate whether a brick will actually fail, but it can be used to decide which design and geometry might be favourable.

Figures 7, 8, and 9 show the temperature distribution and the maximum principal stresses evolving in the tap-hole blocks during tapping for block sizes of 260 mm × 260 mm and 400
mm × 400 mm. The case considers a soft refractory mix combined with refractory bricks as the surrounding refractory, which allows free movement of the blocks over the tap-block height and width. Stresses are shown after 60 seconds of tapping and after 20 minutes of tapping. The simulation shows that the highest thermomechanical stress due to the unsteady-state temperature field after 20 minutes (at the end of the tapping procedure) is on the cold side, regardless of the tab-block size. It can be seen that the larger cross-section reduces the maximum principal stress by a factor of approximately 2. The stress peaks are located at the centre of the outer tap-block edges perpendicular to the tap-hole channel, which can be explained by the deformation of the tap-blocks, as bending is evident from the tap-hole channel over the height and the width of the block. The bending is caused by different thermal expansions due to the temperature gradient in the blocks. Thus, the tap-hole block shape has a crucial influence on the thermomechanical stresses. The position of the stress peaks correlates with the typical crack pattern found in tap-holes. Increasing the tap-hole channel diameter from 80 mm to 120 mm increases the peak stress by around 30% of the initial value, which indicates that wear of the tap-hole channel provokes thermo-mechanical failure of the blocks. Figure 10 depicts the maximum principle stresses for a closed tap-hole in steady state and 2 hours after tapping. The stresses are decreased by a factor of 4 to 6 compared with the end of the tapping procedure, and the location of the highest stress moves to the transition between cooling plate and inner refractory lining.
Steady-state closed tap-hole

After 20 minutes' tapping

After 2 hours' resting

Figure 7. Tap-hole temperature distribution (°C) with channel $d=80$ mm
Figure 8. Tap-hole temperature distribution (°C) after 20 minutes’ tapping with channel $d=120$ mm.
After 60 seconds’ tapping, \(d=80\) mm

After 20 minutes’ tapping, including magnification of deformation, \(d=80\) mm

After 20 minutes’ tapping with \(d=120\) mm

*Figure 9. Maximum principal stresses (Pa) evolving in rectangular tap-blocks during tapping.*
Figure 10. Maximum principal stresses (Pa) at steady state, no tapping; and after 2 hours' cooling.

Figure 11 shows the differences between rectangular 260 mm × 260 mm and cylindrical d=270 mm tap-hole blocks. The cylindrical tap-hole blocks are simulated with two different mechanical boundaries; one that allows a freely moving insert along the cross-section by using a soft refractory mix for comparison with the rectangular blocks, and one that is implemented into a stiff surrounding brick (well block). The circular inserts show a reduction of around 30% for the maximum principal stress during tapping. If the round tap-blocks are inserted into a stiff surrounding brick, the stress peaks at the centre of the outer block edges vanish as they are superimposed by compressional stresses. Instead, the peaks are located at the position of the surrounding brick edges, which show a similar magnitude as the stress peaks of the freely moving rectangular tap-blocks. In reality the edges might have less influence than shown in this model because mortar between the bricks has a certain compressibility and will reduce the stresses.

Figure 12 shows the influence of increasing the number of tap-hole blocks and removing the water cooling for the block size 400 mm × 400 mm with a channel diameter of 120 mm. By increasing the number of tap-blocks from five to ten, the stress peaks are reduced by about 12% and the stress distribution is equalized. Removing the cooling reduces the peak stresses.
by the same percentage. Considering the overall stress distribution, removing the cooling shows a much greater effect. In particular, the blocks inside the furnace show a significant reduction in tensile stresses.

Figure 11. Comparison between rectangular and round blocks.

Figure 12. Maximum principal stress in 400 mm × 400 mm tap-blocks with d=120 mm after 20 min of tapping.
Figure 13 shows the maximum principal stresses for the 260 mm × 260 mm tap-blocks in a mechanically stiff refractory configuration with surrounding bricks, neglecting possible joint compression. Similar to the round tap-blocks, the maximum principal stress peaks on the outer edges are suppressed and move to the edge position of the surrounding bricks. Due to the high stiffness, the principle stress peak in the transition area between cooler and refractory is about twice that in the case of the freely moving tap-blocks.

CONCLUSIONS

A typical tap-hole design for ferroalloys or base metal smelters was simulated to show some fundamental relationships between the tap-block geometry and the evolving thermomechanical stresses. The thermomechanical study illustrates the need for simulation tools for refractory tap-hole design. Even though the model was simplified and several phenomena contributing to tap-hole wear were neglected, some important conclusions can be drawn.

The maximum principal stresses due to unsteady-state temperature fields during tapping lead to peak loads in the tap-hole operation. The specific case showed that the highest maximum principle stresses were attained after 20 minutes, at the end of tapping. This might have implications for the closing procedure and the ensuing forces. This will vary from tap-hole to tap-hole depending on the refractory quality, the general tap-hole dimensions, and the tapping and cooling times.

Depending on the refractory design surrounding the tap-blocks, a different maximum stress pattern occurs. A mechanically flexible configuration with a refractory mix shows stress peaks typically in the centre of the block cross-section at the outer edges. This correlates with typical crack patterns in real tap-holes, as most tap-holes use a refractory mix to enable a sound installation and compensate brick tolerances. The coldest tap-hole block on the outside shows the highest stresses for the flexible configuration. A stiff configuration with bricks and restricted movement leads to a relocation of the stress peaks to the edges of the surrounding bricks and higher stress magnitudes.
An increase of the tap-hole block size leads to lower tensile stresses and less risk of cracking, with the possible drawback of an increased block weight, which might hamper the installation, maintenance work, and (depending on the general tap-hole area dimensions) the cooling of the tap-hole block. Therefore, increasing the number of tap-blocks might be an option as this shows a positive effect on the tensile stresses, but with the drawback of increasing the number of joints.

Removing the cooling results in a general improvement in terms of thermomechanical stresses and the possible risk of crack formation in the tap-blocks. Nevertheless, cooling might help to slow chemical corrosion in the tap-hole area and restrict erosion by reducing the refractory surface temperature or favouring accretion formation. Therefore, a thorough analysis of the major wear mechanisms is necessary to justify the installation or removal of a cooler.

The use of cylindrical tap-hole blocks shows advantage over rectangular ones. By inserting the blocks into a stiff surrounding brick (well block) the overall stress distribution is decreased tremendously, with the drawback of high peak stresses located at the edges of the surrounding bricks. Cracks will initiate at the points where the edges of the surrounding bricks are in contact with the tap-hole blocks, which could be in the middle of the bricks but depends on the arrangement of the bonded lining system.

Generally, a stiffer tap-hole configuration shows an overall improved tensile stress distribution during tapping, with high Hertzian stress from the surrounding brick edges on the tap-hole blocks. The application of mortar might reduce the peak stresses, as well as possible plasticity of the refractory bricks.

For improved design assessments an improved description of the refractory material behaviour is needed to incorporate plasticity of the material and effects like creep under load or stress relaxation.

Another important aspect would be the validation of the modelling work against experimental data. This work compared the stress patterns against a typical crack pattern in a tap-hole block. Besides visual inspection, a comprehensive validation would demand a comparison of strain and stress values and detection of crack initiation as well as monitoring of crack propagation. Due to the harsh environment in a real tap-hole, a test stand for such validation is required. This was outside the scope of this work. New measurement methods and configurations are required, e.g. attaching strain gauges to refractory bricks for strain measurement or using acoustic emission measurements for crack detection in a tap-hole. Besides the improvement of material models, RHI MAGNESITA focuses on developments in monitoring for improving its engineering capabilities.
REFERENCES


Daniel Rene Kreuzer  
*Director of Engineering Services & Development, RHI MAGNESITA*

Daniel joined RHI MAGNESITA, formerly RHI AG, in 2012 and is currently working in the field of refractory design developments. He has managed a number of refractory design and installation projects and gained broad expertise in the field of furnace integrity, refractory design solutions, and simulation. Daniel achieved a Master’s degree in mechanical engineering from Vienna University of Technology in 2008 and started working as a project assistant at the Faculty of Mechanical Engineering in the Department of Energy Systems and Thermodynamics. During this time he worked on energy optimization projects for iron and steel production processes. He was awarded a PhD in mechanical engineering in 2012.