Effects and Analysis of Thermal Stresses on Large Induction Furnace Refractory Linings for Molten Metal Applications

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Introduction:

One of the dominant factors which determine the life of refractory linings in large induction furnaces is the breakdown of the lining caused by various mechanical stresses caused by thermal expansion and contraction. While smaller induction furnace linings are inherently less prone to these issues due to the corresponding reduced scale, larger furnaces (500kg capacity and higher) will see a greater propensity for failure due to these compounding stresses. While improvements in the refractory materials to handle thermal shock are of course beneficial, the actual structure of the refractory lining can also have a great impact on how these stresses are handled. In this paper, furnace structures consisting of monolithic rammed, mortared brick, and segmented brick construction are all compared and analyzed using Finite Element Analysis techniques to determine where and why stresses are formed, and how they can be minimized.

Existing Lining Structures:

While we discuss the structure of linings, it is best to also quickly review the general layout of the coreless induction furnace, which is used for many high temperature molten metal industrial applications and nearly all alloy investment casting production. The basic furnace consists of a metal structure (furnace box) that incorporates a water cooled alternating current coil (See Figure 1) operating at very specific currents and frequencies. Water cooling ensures the integrity of the coil and is a key element in the overall function of the lining. Contained in the coil is the ceramic furnace lining used to contain the metal charge. The coil produces a magnetic field which causes eddy currents to flow within the charge. Resistance heating from this induced current within the metal heats the charge raising the temperature to its molten point, which for many aerospace alloys is around 1,600C.

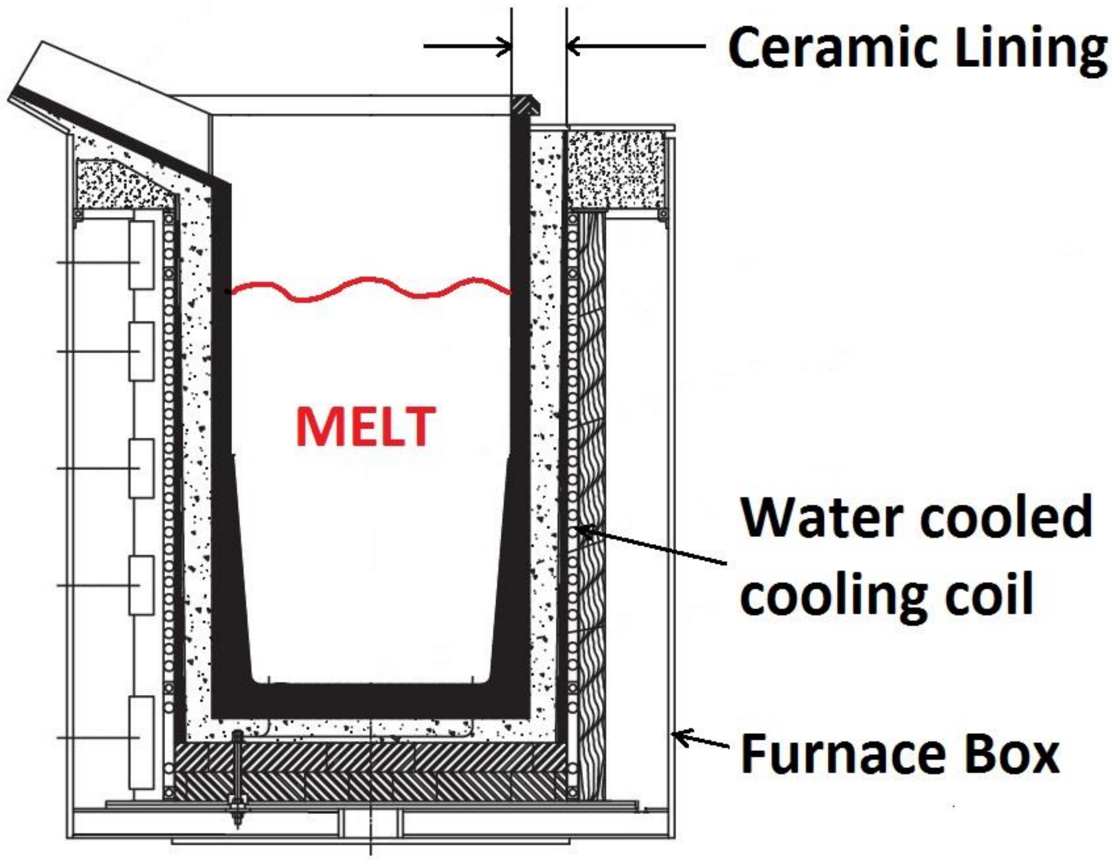

Figure 1

The point to be made here, is with the metal heating from the inside out combined with the continuous cooling of the outer coil, there is a substantial thermal gradient created through the refractory wall. As shown in Figure 2, we can see if we focus on the section of the furnace wall circled in blue and look at a thermal profile of this section shown in Figure 3. We can see that there is a large thermal difference happening in a small distance. This thermal gradient is what gives the lining its molten metal stopping power. The difference in expansion associated with the temperature gradient results in a strain proportional to this gradient. This strain adds to the stress state of the lining.

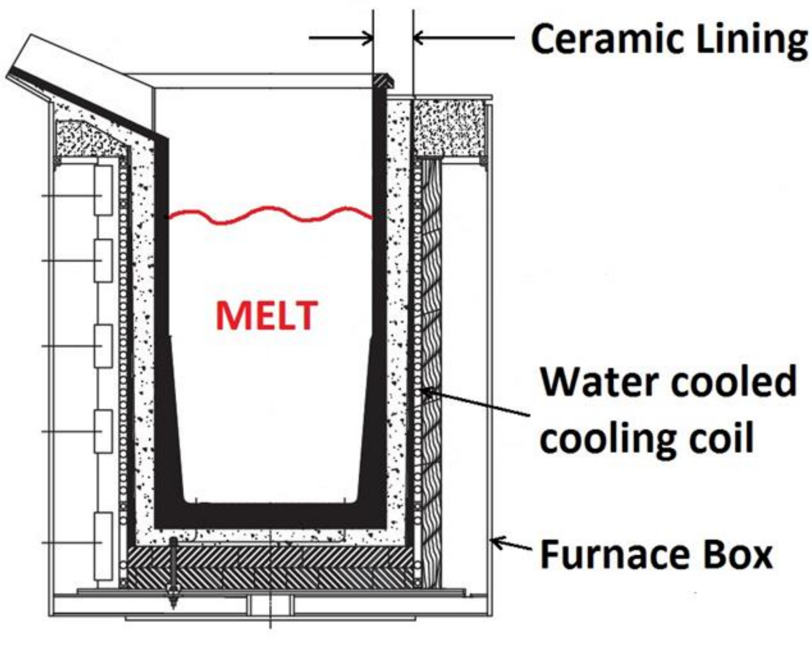

Figure 2

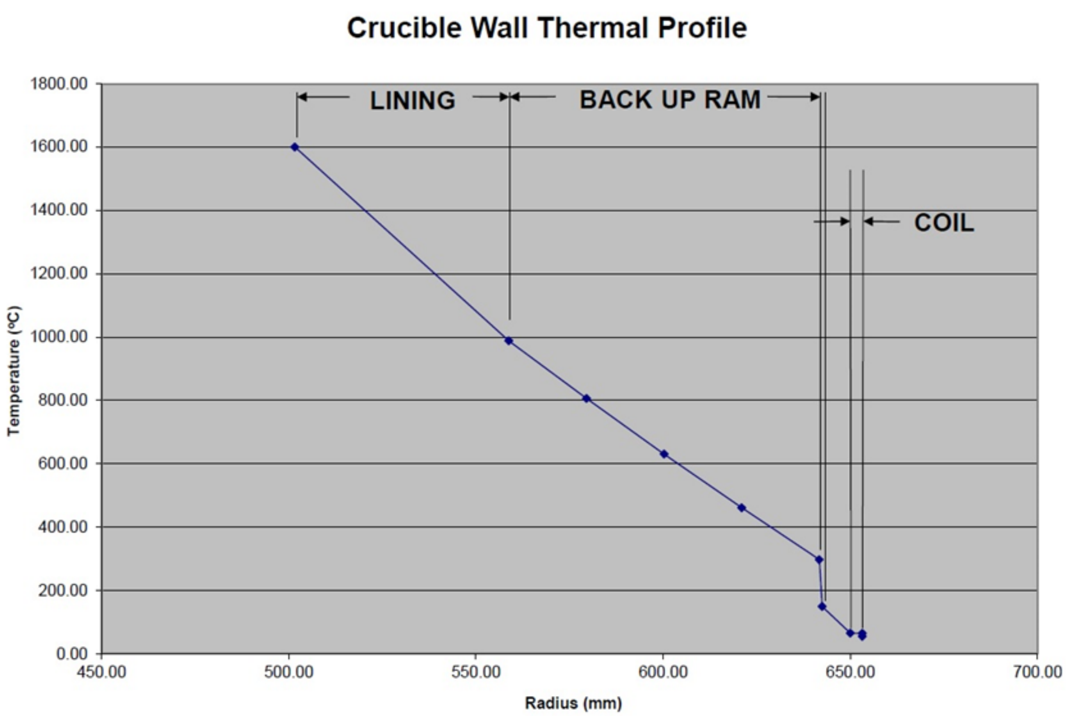

Figure 3

Thermal Stresses Created in the Furnace Lining:

Let’s now investigate the various stresses that are created in lining of this furnace system, and how the different lining structures handle them.

Looking at the expansion on a more macro scale. Because of the high temperature, there is thermal expansion in the ceramic shown in figure 4, both in the vertical and horizontal directions.

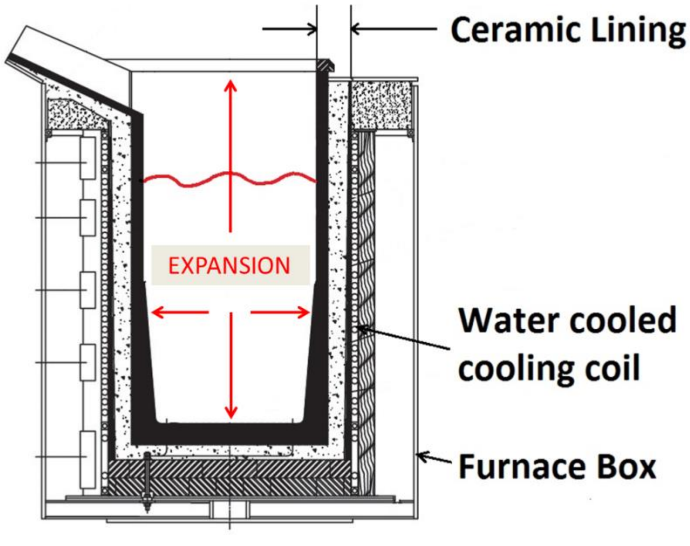

Figure 4

Simplifying the lining as lining as cylinder, we can see that several things are happening to it. For a reference scale, in our example we will look at a 3 ton lining.

As the furnace is heated to 1,600F, the lining material is expanding. The "green" color is shown in figure 5 is the starting size, while the light red color shows its expanded size after heating.

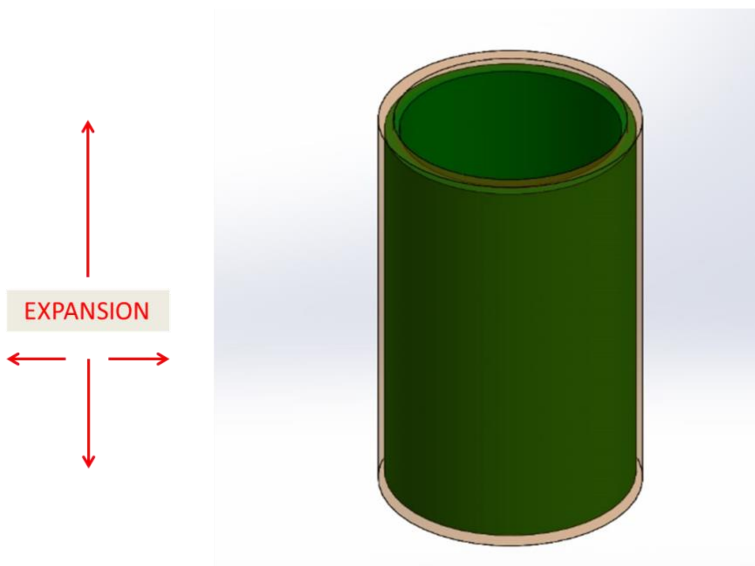

Figure 5

Now as the lining is constrained in the bottom, this vertical expansion goes up from the base. For an Alumina or MgO based material, the height of this lining will expand as much as 7mm.

Further note that the lining ID expansion is proportionally greater than the OD expansion because of the thermal gradient through the lining wall. This constraint results in stress and compression on the ID and tension on the OD surface.

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Using Finite Element Analysis (FEA) as a tool:

To better understand the stress imparted on the lining during service a finite element analysis (FEA) was performed on this model. This FEA took into account the thermal gradient seen across the lining as well as the static loads seen in service. Monolithic rammed, mortared brick, and segmented brick construction were all compared and analyzed to determine where and why stresses are formed. The input conditions of the analysis were kept identical for all three simulations, with the only variable being the lining construction.

Figure 6 shows the resultant stress seen by a monolithic rammed lining in service. The color scale shows von Mises stress, which takes into account the three dimensional complex stress state.

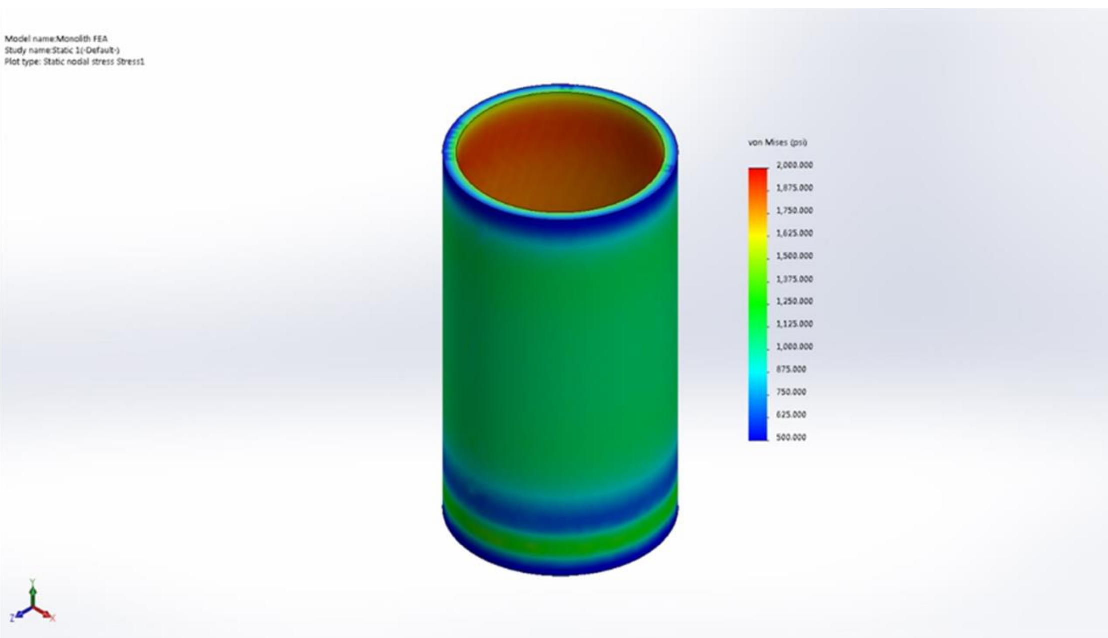

Figure 6

Von Mises stress is more exact for ductile material than brittle materials, but is still very useful in yielding comparative data. The FEA results show the ID of the lining experiencing a higher stress than the OD, which occurs because of non-uniform thermal expansion. This stress will weaken the ceramic grain boundaries, and if significant enough result in cracking throughout the monolithic lining. The cracking of the lining results in a series of smaller components, which can grow and expand independently and reduces the overall stress of the body.

Figure 7 shows the resultant stress seen by a mortared brick lining in service. The color scale shows von Mises stress on the same scale as figure 6.

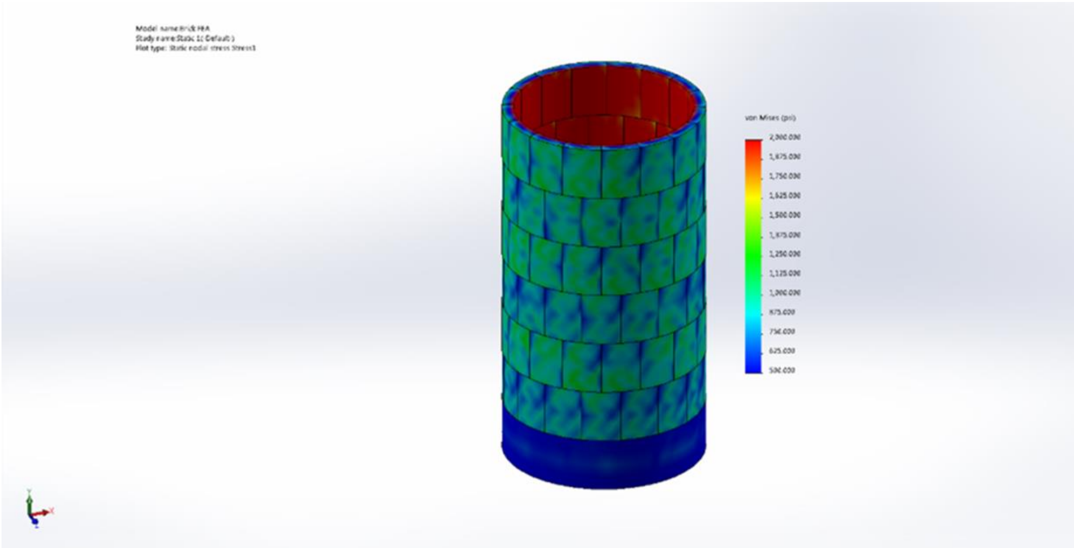

Figure 7

In general, the max stress seen by the ID of the mortared brick lining is similar to the stress seen by the monolithic rammed lining. This is expected, since the mortared brick will act as a singular body, up until the point where the thermal stress causes the weakest portion of the system (the mortar) to break.

Failure (cracks) due to Thermal Stresses:

It is no wonder that a rammed, brick, or one piece lining acting as a one large unit will crack and spall given the thermal forces that are put upon it as shown in the earlier examples. These cracks are all too well known by foundry men who have to repair, patch or replace furnace linings as shown in Figure 8. As a compounding issue, when the furnace has this cracking phenomena and cools, the molten metal can now move into these cracks filling them. Then when the furnace is re-heated, the metal expands, making them even larger which compromises the integrity of the furnace lining.

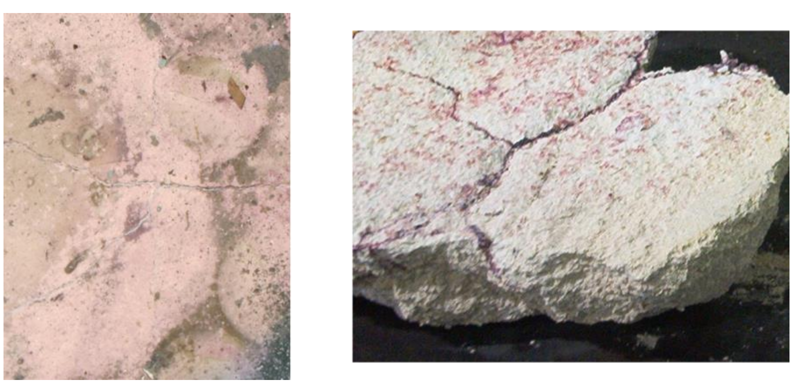

Figure 8

The examples so far demonstrated the thermal stress results of a one piece, rammed lining or a mortared brick lining, which mostly behave as a one-piece entity for stresses. What are ways that we could better allow for the expansion in the system?

Segmented Interlocking Brick Assembly:

What if we reduced the assembly into non-mortared interlocking bricks?   In order to best accommodate thermal growth, every block should manage its own thermal expansion and the entire system must be mortar free, but for stability reasons must be completely interconnected.

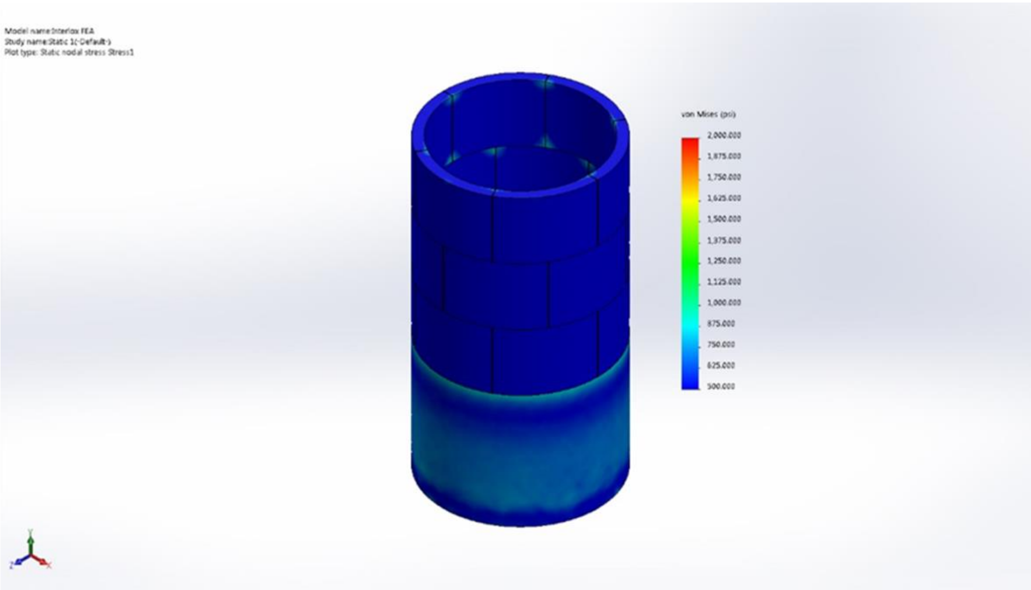

Figure 9

Figure 9 above shows the resultant stress seen by a segmented brick lining in service. The color scale shows von Mises stress on the same scale as the earlier figures. The individual segmented bricks have engineered expansion gaps such that the body expands in service until all gaps are closed, taking into account the differential thermal expansions of the ID and the OD. At operating temperatures, the body sees a much lower overall thermal stress as compared to the two previous lining options. When the operating temperatures cool the segmented bricks will shrink back to their original size.

Integrated Furnace Hold Down System:

While the interlocking non mortared bricks help to dissipate the stresses, how do we deal with the growth of the lining? This integrated furnace hold down system shown in figure 10 utilizes a spring loaded hold down system consisting of a top clamp and interconnected spring system into the furnace.

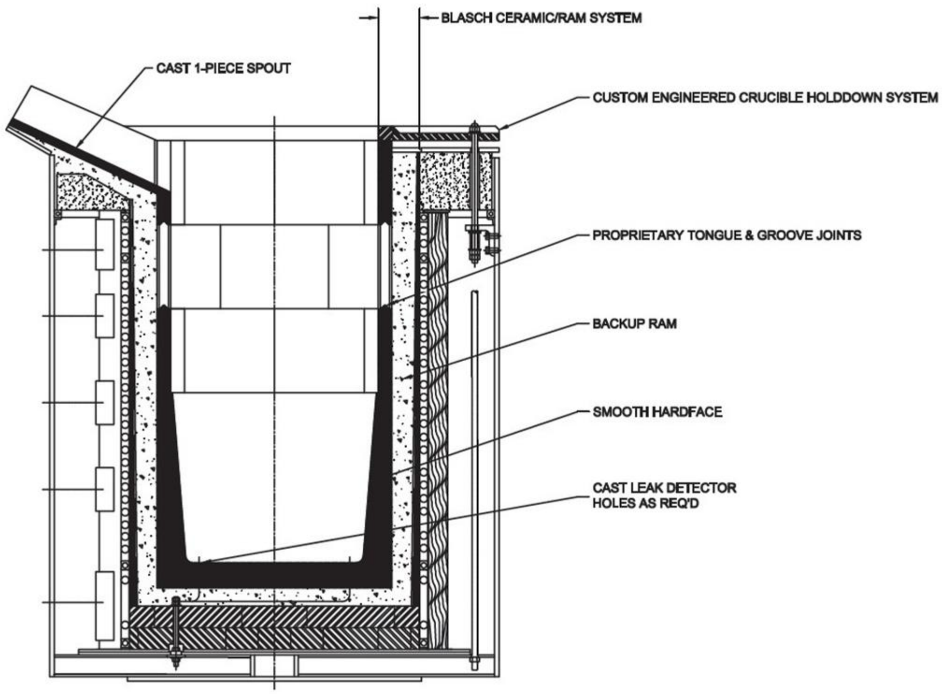

Figure 10

This system can be calculated to provide the proper pressure to allow the system to expand and contract while the furnace is run through its complete cycle for the melting process.

Lessons Learned:

As we have seen through the FEA work, this segmented component approach reduces thermal stresses caused by the induction melting process. Specifically, the segmented lining system reduces the horizontal and varied stresses by using the unique segmented and interlocking brick approach backed by the ramming system. It then holds the vertical expansion in check by allowing the lining to grow and contract using the integrated furnace hold down system. As shown in figure 11, it is easy to see this segmented component system provides mechanical advantages to deal with the adverse temperatures required with high temperature alloys.

COMPARISON:

One Piece **Mortar Brick** **InterLok™ Segmented**

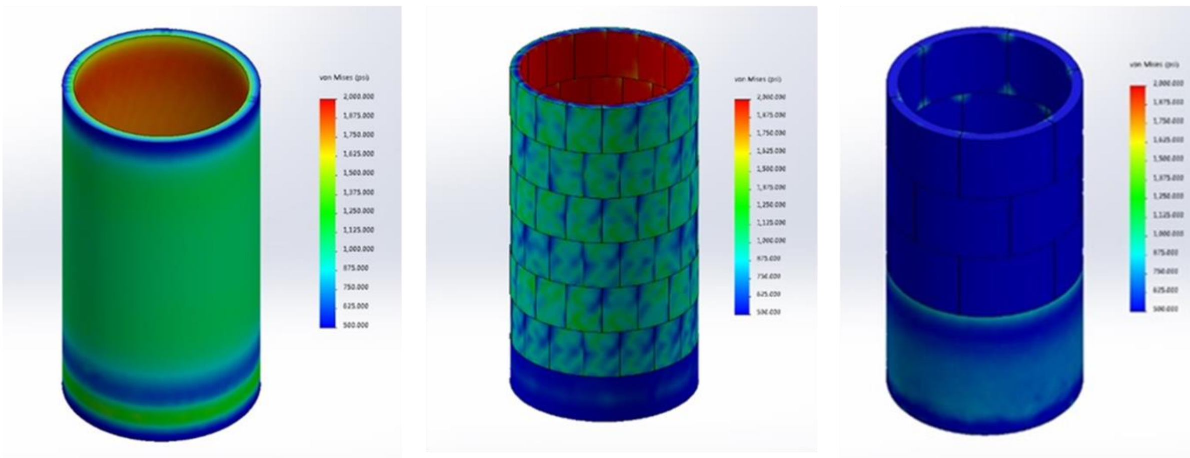

Figure 11

Plans have been made to take more detailed information from this study, and use this to improve the InterLok lining system further.

This research has shown the benefits of using a segmented ceramic lining system that can expand and contract without cracking, integrated with a spring hold down system. It behooves us to review what other ceramic systems can be designed that will benefit from this type of integration.