Numerical Method for Laser Welding Simulation

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Abstract: Numerical methods using Abaqus to simulate welding processes have been available for several years. These methods typically are based on arc welding procedures where one is depositing a bead or beads and the interest is in the thermal/stress history in the local heat affected zone. The significant thermal cycle found during welding does introduce residual stress in the structure. This residual stress must either be managed with a post weld heat treatment or the welding process and variables must be adjusted to minimize residual stress.

This method is different in that laser welding does not typically deposit any material and the thermal/stress zone of interest is not directly in the weld zone but some distance away where the combination of heat and material differences can cause material failure. In this paper, a method is described showing how to simulate a laser welding process using capabilities and tools found in Abaqus and Abaqus/CAE. The method allows sequential pulsing of the laser energy with all the typical laser welding variables such as pulse energy, pulse duration, travel speed, welding pattern, material and thermal properties.

While the laser pool is not modeled directly, the heat and stress effect throughout the rest of the structure is determined. The finite element thermal results are validated against direct temperature measurements. Examples are presented and compared with each other and the direct measurements.

Keywords: Laser, Welding, Thermal Stress, Heat Transfer, Implantable Medical Device

1. Introduction

Simulation of the welding process has been available in Abaqus for several years. These simulations are for welding processes associated with depositing beads of material with multiple passes where the residual stress in the heat affected zone is of most interest. Any thermal effects away from the weld area are typically of much less interest.

A review of available literature did not reveal other welding modeling techniques that could be of use. Therefore, this paper presents a method to deal with a different type of welding process. Laser welding, which is often associated with small medical devices, causes parts to be fused together without the introduction of any additional material. Also, the zone of interest is not directly in the weld zone but rather some distance away. The heat from the welding process causes thermal stress issues with other components. By simulating the laser welding process and the myriad of variables, one can optimize the process and minimize thermal stress affects.

1.1 Background

A medical device manufacturer of a new, implantable product that required electrical connections, was having difficulty maintaining a hermetic seal within their product after a laser welding process. The hermetic seal is critical for device longevity within the saline rich environment of the body. Compounding the problem is the fact that the laser welding process is near the end of the manufacturing process and therefore failures at this point result in the scrapping of high value-added components.

The initial investigation revealed that the laser welding process appeared to be creating a solid/stable weld. Ceramic materials, however, that were insulating the electrical conductors, appeared to be cracking. It was believed that the thermal effects of the welding and the uneven heating and thermal expansion of components were causing the thermal stress cracking. Attempts at iteratively adjusting laser welding parameters were met with very limited success. There was a need to understand more fully what was happening with the components and thus a desire to simulate the process.

While it would be very interesting to reveal details about the part or product being modeled, this author is restricted in revealing details that would identify the product, critical materials or company. As such, this paper is necessarily restricted to revealing the method without disclosing the product details.

1.2 Laser Welding

There are a variety of laser welding technologies but often, the laser is pulsed at a particular frequency, energy density, period and traverse rate. Figure 1 illustrates a typical laser welding pattern with multiple overlapping weld pools. The quality of the weld penetration is often determined by sectioning the weld as shown in Figure 2. Depending on the gap between the parts and the joint design, the weld zone may be at a different level than the surrounding material. More importantly, no addition or removal of material occurs during the laser welding process.

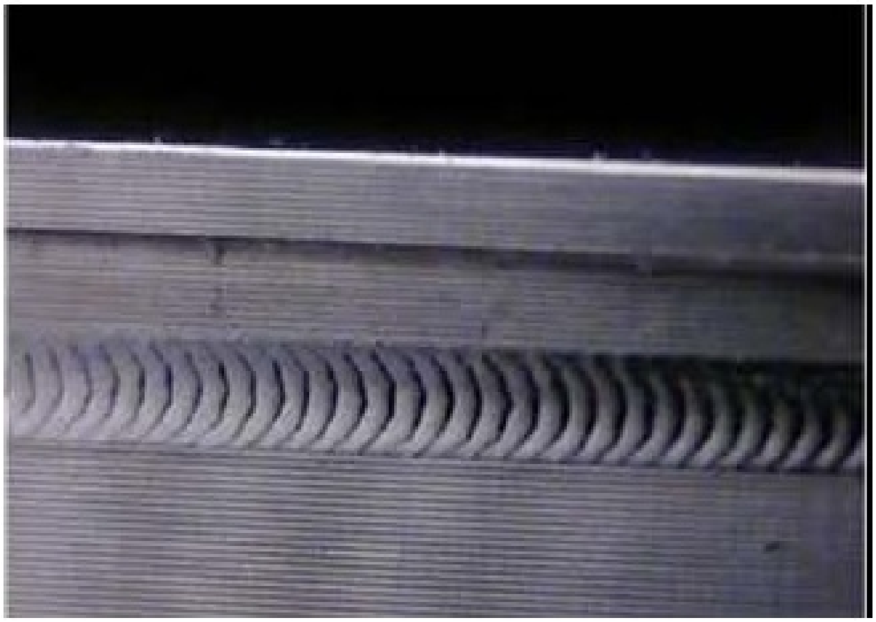

Figure 1. Typical laser welding pattern

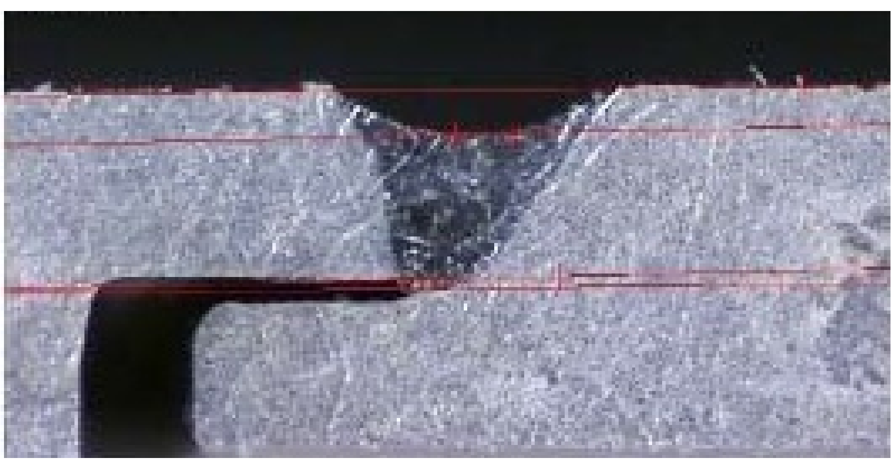

Figure 2. Cross section of typical laser weld

2. Analysis Model

Throughout this paper, images of an analysis models are shown to demonstrate the method used to model the laser welding process. Images of any complete medical device or specific material information are purposefully omitted for confidentiality purposes.

2.1 Model Description

The overall analysis model is illustrated in Figure 3 while a detail view of the analysis model is shown in Figure 4.

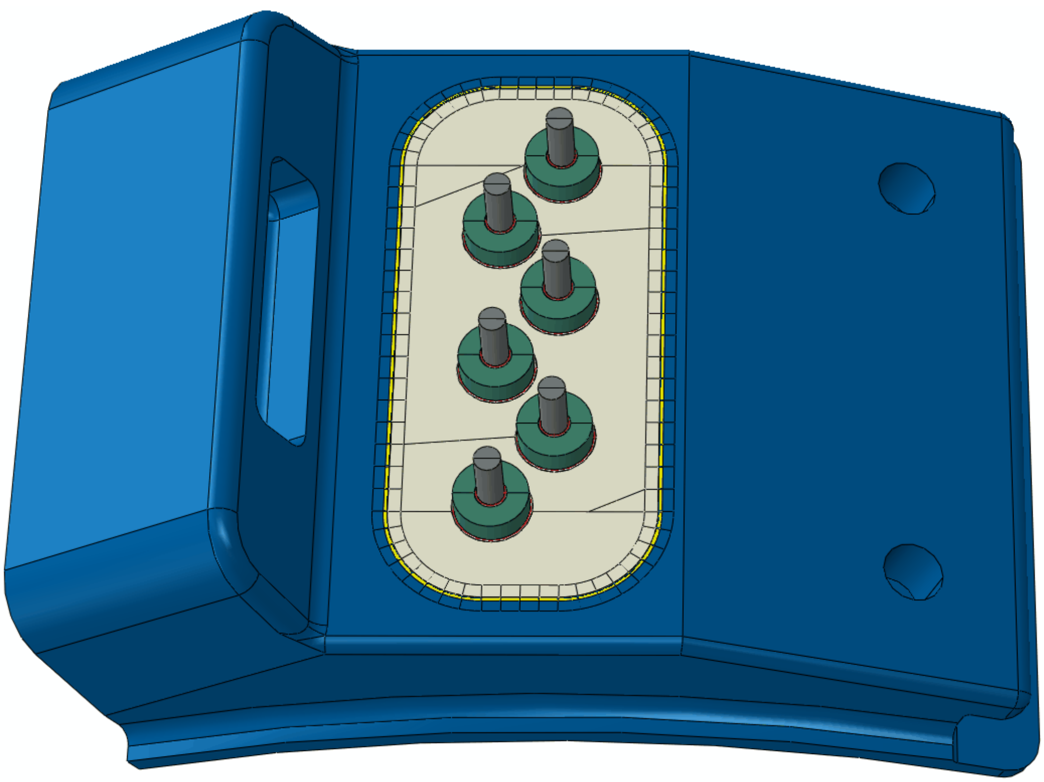

Figure 3. Analysis model

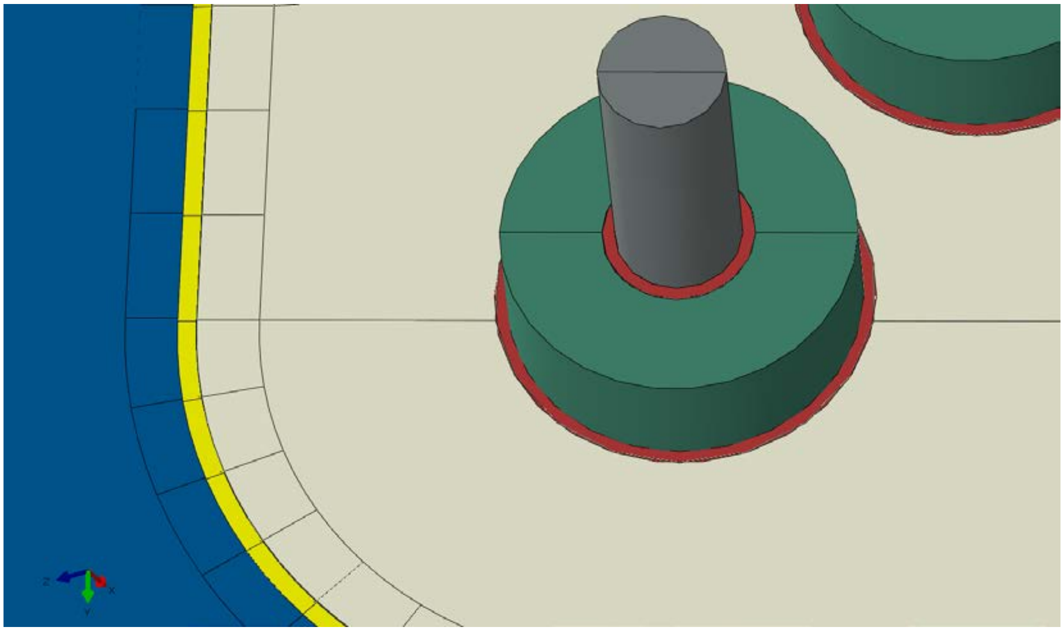

Figure 4. Analysis model detail

The blue and beige parts are titanium and are to be welded together. The gray cylinders are the platinum electrical connectors while the green and red parts are ceramic like materials. It was suspected that the green and/or red parts were cracking during the welding process causing the hermetic seal to be compromised. The yellow material represents the gap or the weld bead between the two titanium parts depending on the time during the welding process. It is modeled as a hyper-foam material to allow low force relative movement of the two titanium parts being welded but allow heat transfer between the two parts as one would expect when welded together.

As illustrated in Figure 4, along the welding path, parts are partitioned on the surface in a matching pattern. This can be accomplished directly in Abaqus/CAE. These discrete zones are used to apply the laser energy to the parts at the correct heat flux, rate and location to match the physical laser welding process.

2.2 Material and Film Properties

As in any thermal-stress analysis, all the parts must be defined mechanically and thermally. Therefore, elastic modulus, density, conductivity, expansion coefficient and specific heat must all be defined. Thermal properties of all the parts and/or surfaces must also be specified to define the starting temperature, convection coefficient and emissivity to include radiation effects.

2.3 Welding Process

2.3.1 Overall Method

During the actual welding process, the laser beam is pulsed and traversed along a particular pattern resulting in material being fused together and thermal energy being transmitted to the parts. There are hundreds of partially overlapping pulses creating a welding pattern as illustrated in Figure 1. Initially, the two parts are only in proximity to each other but are not mechanically or thermally connected in any significant way. As thermal energy is applied to the parts, expansion can occur and relative motion between the parts does occur. As the welding proceeds and the weld pools solidify, the two parts are intimately connected in the areas that have been welded but still only in proximity in the other regions. Eventually, at the completion of the welding process, the two parts are fused together both mechanically and thermally.

The welding process is simulated by creating a series of zones where energy will be applied. In the example illustrated, there are 76 zones along the weld path. These 76, non-overlapping zones are modeled to simulate hundreds of overlapping zones found with the actual welding. Each zone is subjected to a surface heat flux for a particular period of time that represents the welding beam in that zone. This time period corresponds with the Step time period of the analysis and is also linked with the actual welding time. Therefore, for this example, with 76 zones, there are 76 Steps defined in Abaqus with the total time period of 10.5 seconds for the analysis which matches the actual time to laser weld the part.

This simulation, using only 76 zones, therefore energy is applied to the part in a coarser way than the actual welding process. More zones could be used certainly with the corresponding increase in required setup time. However, conduction within the parts tends to smooth out the energy application so it would be up to the analyst to determine what level of detail is required.

After one zone is subjected to the heat flux, the heat flux in that zone is set back to zero but the next zone in the welding pattern is subjected to the heat flux for the next Step. So, the welding is simulated by creating a series of high heat flux surface zones along the weld path. This process continues through all 76 zones with 76 Steps in the analysis. As the weld proceeds through the many Steps, temperatures rise in the parts and stress develops due to the temperature gradients and material differences.

An important feature of the analysis is that as the welding proceeds, zones that have already been subjected to the heat flux and presumably welded, are linked together. Areas that are not welded together, continue to be able to move freely relative to each other. This is accomplished with couplings and translator connectors and describe more fully in subsequent sections.

2.3.2 Welding Zones

While the actual laser pulses at a typical rate of 20-30 pulses per second, as shown in Figure 1, with pulses partially overlapping, this example simulation uses 76 non-overlapping zones. While the simulation pulse pattern in coarser than the actual pattern, because the stress zone of interest for the simulation is many pulse widths distant, the smoothing caused by the conduction in the material makes the difference insignificant. Figure 5 illustrates one welding zone with surface area on both titanium parts and the yellow filler material highlighted in red.

This method could be adapted to have overlapping zones with as fine a detail as desired. Defining the zones, coupling, translators, Steps and loading conditions can be quite tedious. So, one would have to balance that time and effort against the resulting change in simulation fidelity.

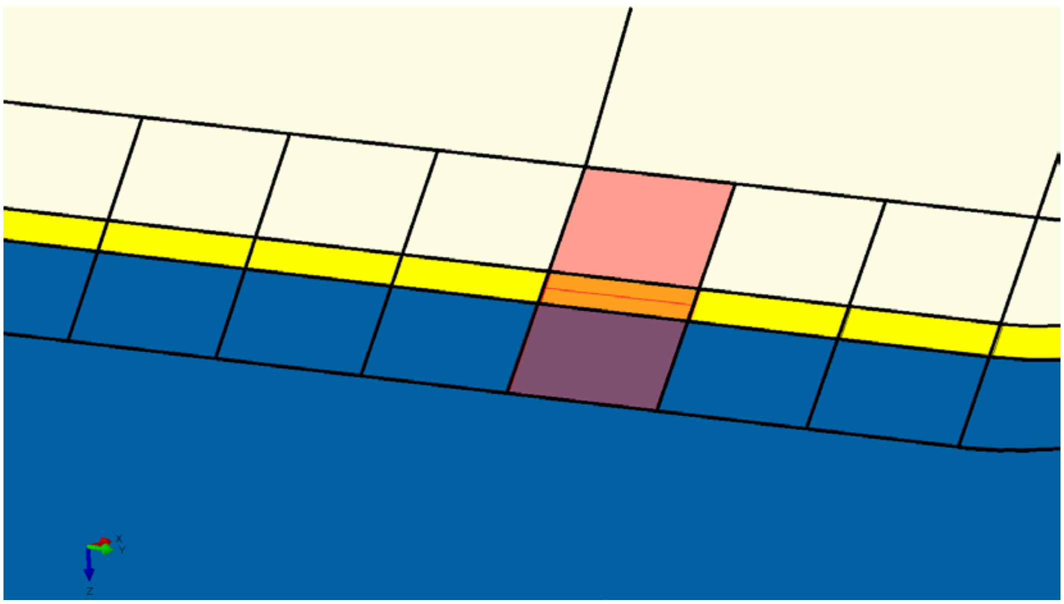

Figure 5: One welding zone highlighted

Using partitioning tools in Abaqus/CAE, one can create welding zones with approximately the same surface area and linear distance along the weld bead. This makes it much easier to define the energy input on each zone. In the example illustrated, the straight and curved zones, as shown in Figure 4, have two different surface areas to be accommodated and two different linear distances along the weld path. Therefore, the *Amplitude definition for the heat flux are different for the straight and curved sections. Similarly, the Step time for the straight zones vs. curved sections are different too but tied to the traverse rate of the laser welder.

2.3.3 Energy Input

The laser welding vendor can provide information about the welding process such as pulse frequency, pulse duration, laser energy and linear travel speed. Using a spreadsheet or a hand calculation, one can calculate how much energy will be applied to each welding zone.

Typically, the laser energy specified is the energy output from the laser and measure with an Ophir meter. One significant unknown is how much energy is actually absorbed by the parts vs. how much is reflected from the surface. This is dependent on material and material surface characteristics but a value of only 25-50% is not uncommon. So, a percentage of the laser output energy is input in the LOAD module as a Surface Heat Flux in the weld zone during the time specified for each Step.

2.3.4 Welding Fusion

The fixing of the two parts together after welding energy is applied to each zone is a critical part of creating a realistic simulation. As parts are welded, they become more constrained and thermal stress effects can occur more readily. One effective method is presented below. Alternative methods are unknown but possible and they are beyond the scope of this paper.

For each welding zone, kinematic coupling are created at the edges to couple the many nodes along the edge to one point. This is done at the leading and trailing edges of each welding zone on both the inside and outside parts. The kinematic couplings are illustrated in magenta in Figure 6 in the schematic of Figure 7. Next, a translator connector is defined between each pair of coupling points linking the inside and outside parts. A translator connector is essentially a one dimensional connector that allows or constrains motion between two points. No boundary conditions are specified for the connector until the weld has traversed past its position. This allows translator to move freely and not constrain in any way the coupling nodes on the inside or outside parts. This also implies that the inside and outside parts may move freely relative to each other when there are no constraints on the connector.

Once welding energy is applied to a particular zone, the trailing edge of that zone would be expected to solidify and freeze in its current position. During the simulation, once welding energy is applied to a particular zone, a no velocity constraint is applied to the trailing translator connector which essentially freezes the inside and outside parts together at the current location. This constraint on the connector remains in place for the remainder of the simulation.

Therefore, as the welding simulation progresses from zone to zone, the most recent zone where energy is applied, is fused together with the constraint on the connector. Other translator connectors on the assembly are not constrained and do allow the parts to move relative to each other in response to the thermal effects of the welding process. By the end of the simulation, all the connectors are set with a no velocity condition which locks the parts together at the many discrete zones.

A potential alternative, that was not explored, would be to tie together surface areas in zones instead of lines of nodes. With the couplings applied to a broader area, the fusing of the parts may be more significant and appropriate for some applications.

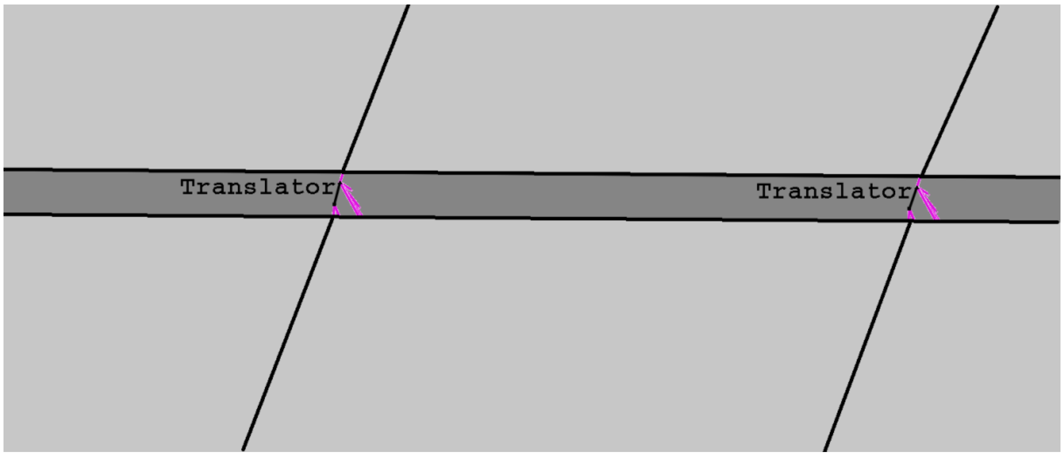

Figure 6. Welding zone couplings and translator connector

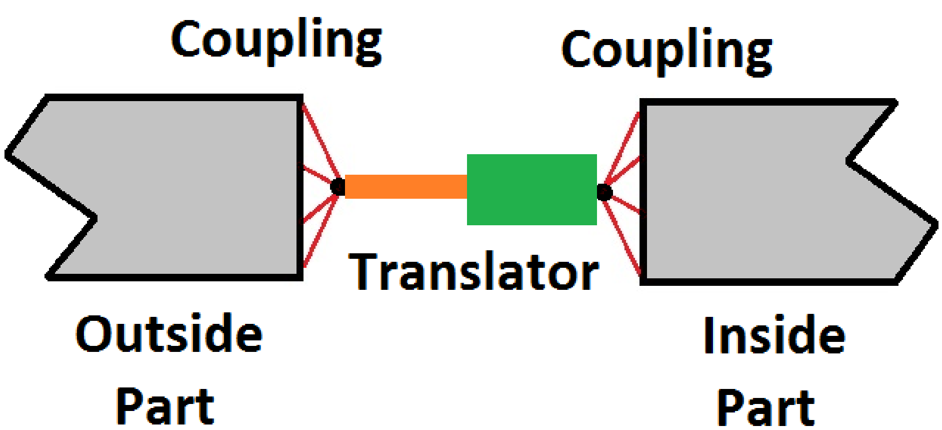

Figure 7. Schematic of welding zone connections

2.3.5 Conduction Across the Weld Bead

Between the two parts being welded, there is a separate part that fills the gap between the parts. This part is illustrated in Figure 4 and Figure 5 in yellow. This material is important in that it allows conduction across the weld bead which could be significant. This material also must allow the two parts to be welded to move relative to each other as uneven thermal expansion occurs. By using a soft hyperfoam material with the same thermal properties of titanium, the titanium parts can move easily and also conduct across the gap.

One limitation is that the conduction ability is possible at all times. So, even before the heat flux has been applied in a zone, conduction is possible through the yellow hyperfoam material. Considering the speed of the welding process, this does not appear to be a significant limitation that would affect the results in this example.

3. Results Comparison

3.1 Temperature Contours

Figure 7 through Figure 9 illustrate temperature contours in the assembly near the beginning, middle and end of the welding analysis simulation example. One can observe that the temperatures are highest in the zone of high heat flux where the welding is occurring. Additionally, temperature gradients can easily be observed across the ceramic components insulating the electrical connectors. Lastly, as the analysis progresses, the overall temperature of the part increases from the initial temperature shown in dark blue.

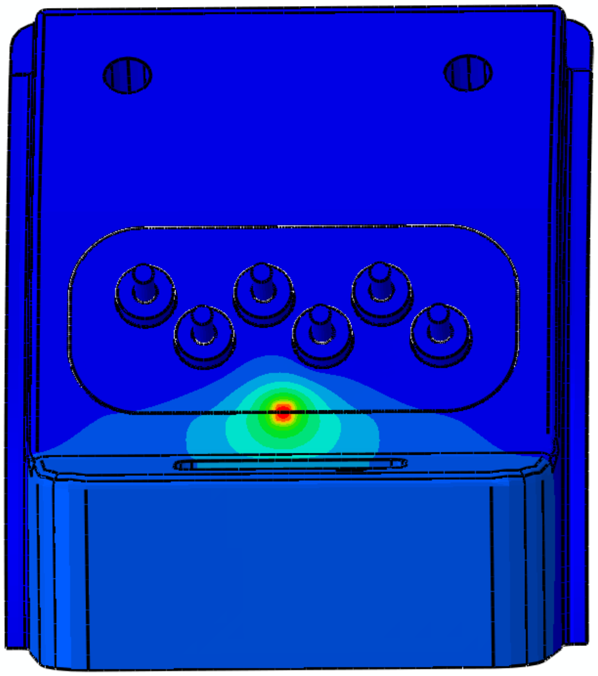

Figure 8. Temperature (NT11) contour at end of first step

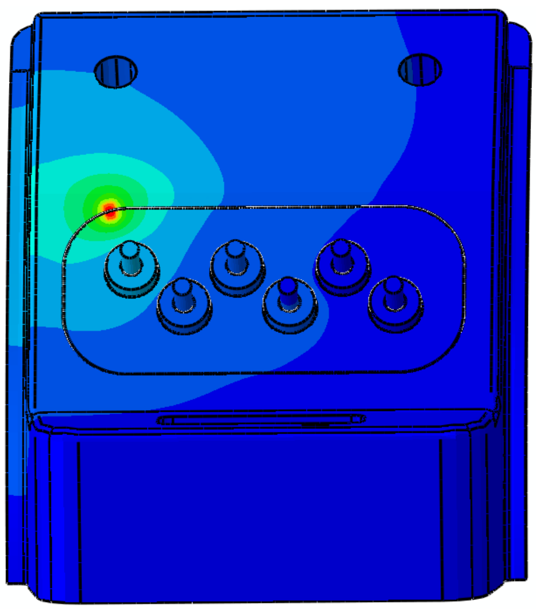

Figure 9. Temperature (NT11) contour partially through the analysis

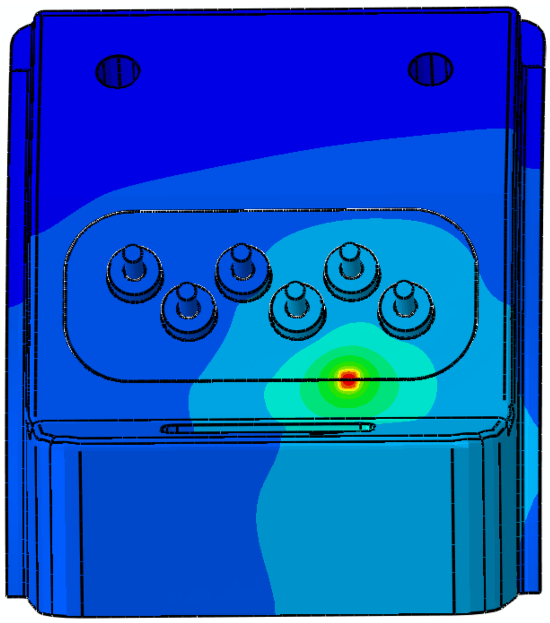

Figure 10. Temperature (NT11) contours near the end of the analysis

3.2 Temperature Comparison

There is a plethora of variables associated with this simulation analysis with some of them not easy to quantify. Some key variables include convection coefficients from the free surfaces, emissivity and the amount of laser energy reflected from the surface and thus not absorbed by the parts. While one could undertake an extensive testing effort to quantify these values with more specificity, that significant expense is likely not necessary. Since the goal of this analysis is to reduce stress in some components, as long as the physics is correct and the temperatures approximately correct, relative stress values should also be correct.

During this evaluation, some test articles were instrumented with thermocouples during the laser welding process. Considering the part illustrated to be welded is less than 12mm across, fixturing and measurement issues are themselves challenging with several potential causes for inaccuracy. Figure 10 shows the testing results during the welding process. Figure 11 shows the simulation results overlaid with the testing results. While the curves do not match directly, the peak temperature for both are in the 160 – 200 degree C range. Therefore, while not a strong direct comparison, the testing and simulation are yielding results similar enough to do comparative stress evaluations.

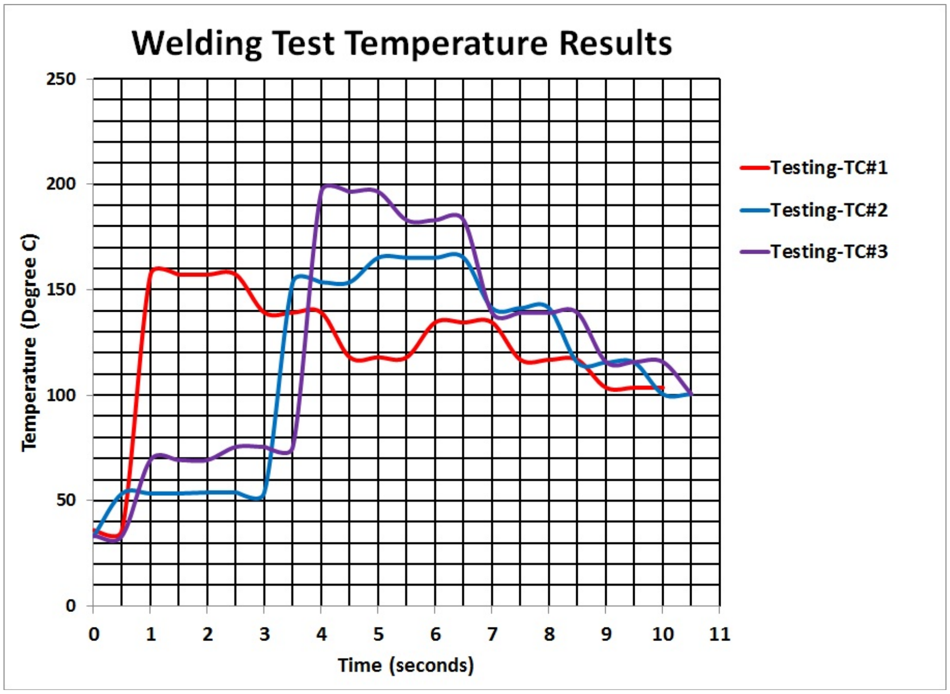

Figure 11. Testing temperature result during welding process

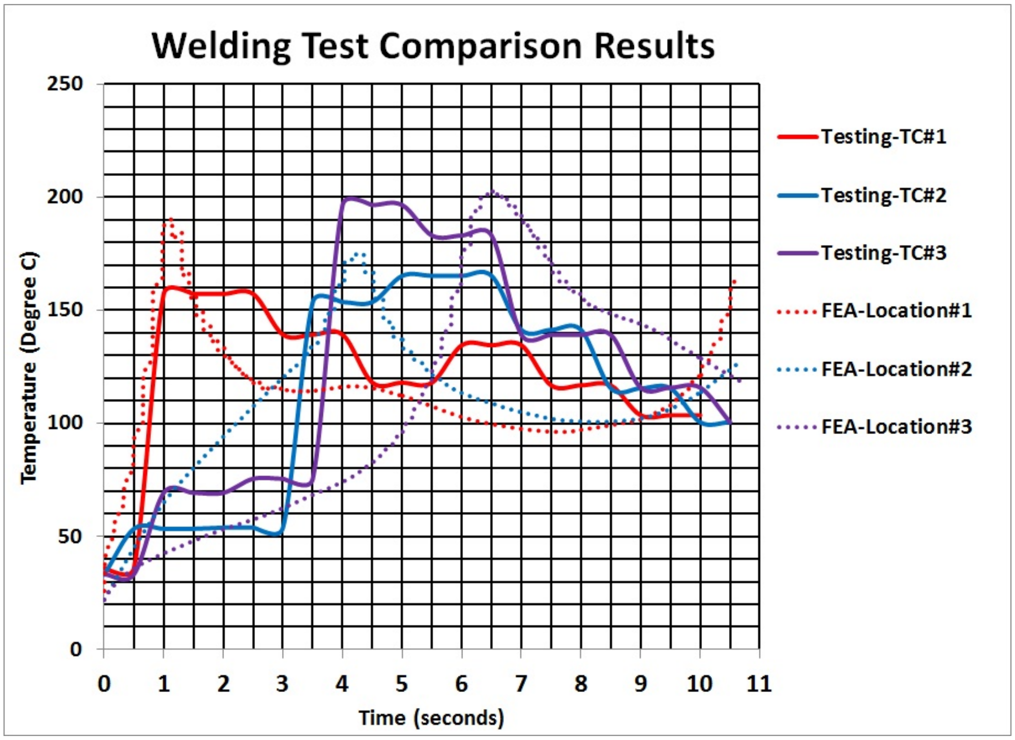

Figure 12. Welding test comparison between testing and simulation

3.3 Stress from Temperature Gradient

A key goal of this analysis is to determine the stress field so that welding parameters could be adjusted to minimize stress and therefore minimize cracking issues with the ceramic components. Figure 13 illustrates the temperature contours at an electrical connector when the welding process is passing nearby. There is clearly a significant temperature gradient in the vicinity of this electrical connector.

Figure 14 illustrates the stress field at the exact same time step as shown in Figure 13. Problematic stress is building in a brittle material with previous testing showing cracking in this same area.

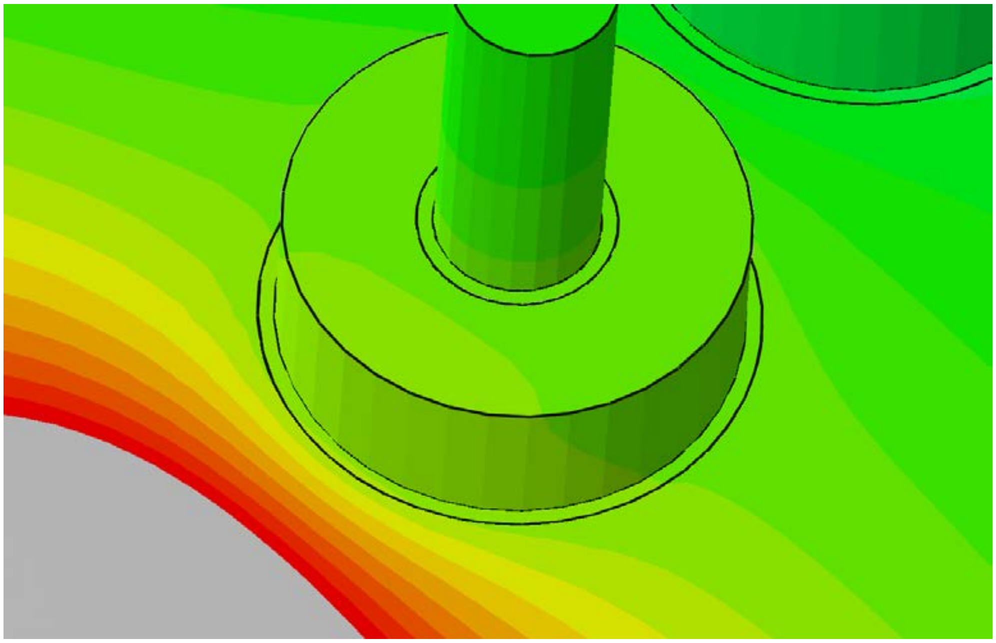

Figure 13. NT11 temperature contours as weld zone passes near electrical connector

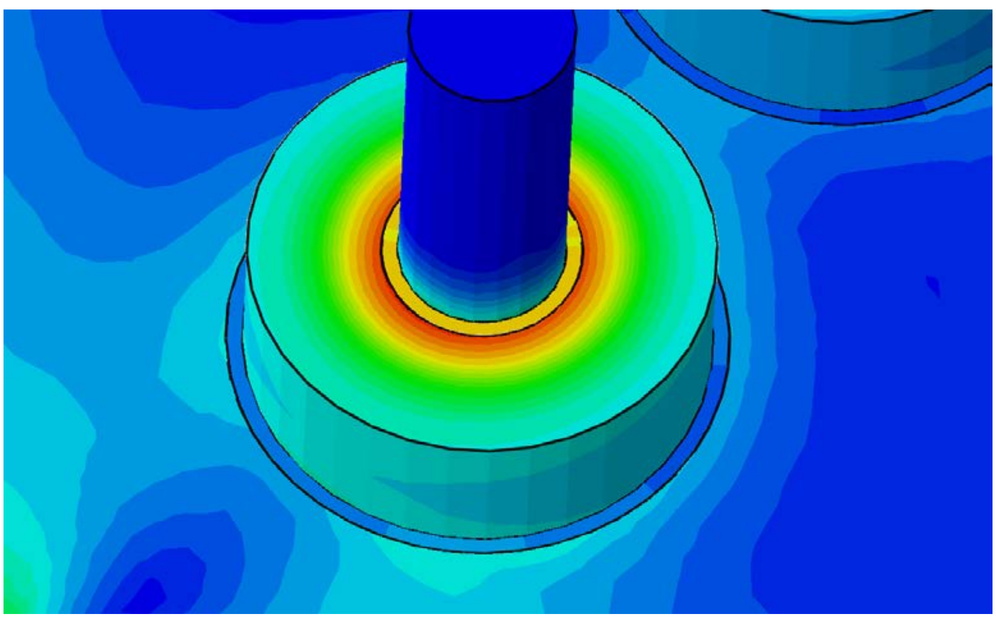

Figure 14. VonMises stress contours corresponding to Figure 13

4. Discussion

The modeling was able to recreate high stress conditions in known areas where cracking has been observed on the physical samples subject to the same welding conditions. The next step was to adjust some of the parameters associated with the welding process, re-run the analysis and observe the changes. Varied parameters include welding speed, welding energy input, welding pattern, cooling of components, and component dimensional changes.

For example, efforts to convectively cool the part during the welding process were met with very limited success. Adjusting the convection coeficients within the modeling, also showed little changes in temperature or stress. Changing the welding pattern had some effect. For example, instead of welding in a continuous pattern around the weld path, the welding stepped among a scattering of zones around the part that were eventually all fused together. Changes to welding energy and pulse rate can be effective but there a limits while still creating a solid weld. Adding some details to the parts to help restrict heat conduction was also somewhat effective. Many of the ideas listed were modeled with results compared to baseline results. By making adjustments with the modeling, when more parts were eventually welded and tested, part cracking issues were eliminated.

5. Conclusion

This paper presents an alternative method to simulate a welding process. The key requirements are that material deposition during the process is minimal and the zone of interest either thermally or structurally is some distance away from the weld zone. There is also a limitation that conduction across the weld gap is available at all times. If the simulation problem presented has similar features, this method could very well be used to simulate a range of welding processes and materials.