Optimization of Heavy-Duty Cylinder Head Gasket Manufacturing Press Using Isight

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Abstract: *The production of heavy-duty cylinder head gaskets requires processing large sheet materials in a relatively short amount of time. In many cases, there is a need to quickly heat the materials to a consistent and uniform temperature. This high-volume process contrasts with a typical heated-press molding operation where the time required for each press cycle is much longer, on the scale of multiple minutes rather than seconds. Raw material weight of several kilograms and a required temperature increase of more than one-hundred degrees Celsius cause the power supply and control requirements to be very complex. Modification of platen designs and development of a new process require unique simulation techniques to optimize the process and equipment.*

In this paper, Isight and Abaqus are used to simulate and improve the multiple-stage manufacturing process of heavy-duty cylinder head gaskets. An iterative procedure using Abaqus with custom scripting is first used to identify the required power input to achieve steady-state press operation. An Isight process flow is then developed to simulate the manufacturing process of coils of material being fed into continuous process equipment and automatically bonded in a heated platen press simulated by Abaqus. Isight parameter studies are then applied to examine the heater power required to maintain a consistent temperature on the platens to minimize both heat loss and press stabilization time. The combination of Abaqus and Isight is used to improve both the heavy-duty gasket manufacturing process performance and the resulting product quality.

Keywords: *Design Optimization, Heat Transfer, Optimization, Output Database, Postprocessing, Powertrain, Seal, Parameter Study, Manufacturing, Composites*

1. Introduction

Many processes involved in the manufacture of automotive components require the input of heat in a controlled manner. Some examples include the cure of a coating, injection molding of plastic components, and adhesive cross-linking. These processes almost always involve several different variables which will affect both the speed of the process and the quality of the finished product. It is imperative to design the process and equipment in such a way that both the time involved and the part quality will meet the required criteria. One such automotive component in which the process and equipment design play a crucial role is the manufacture of heavy-duty cylinder head gaskets for use on diesel engines.

Today's diesel engines produce high engine firing pressures and elevated temperatures. These demands can place stress on the cylinder-head gasket. In the gasket design process, it is necessary to choose a material that matches the application requirements. Materials used to make heavy-duty cylinder head gaskets must be relatively thick, strong, and conformable. It is common to combine several different types of materials, such as steel and graphite, into one multi-layer composite in order to meet these requirements. Victocor® cylinder-head gaskets use a patented material capable of withstanding these high cylinder pressures and elevated temperatures where other gaskets fail.

1.1   Victocor® Cylinder-Head Gasket Design

The Victocor® cylinder-head gasket is composed of five layers (shown in Figure 1). A perforated steel sheet is adhesively bonded to each side of a thick steel center layer, and thin layers of graphite are mechanically bonded to the perforated steel sheets to form the outer surfaces. This results in a solid center layer to support combustion pressure and thin graphite layers to seal fluids. The center layer provides support to the combustion seal and stabilizes flange motion. As a result, high blowout resistance and exceptional flange durability are achieved. Conventional wire rings are used to seal combustion openings, providing a seal with high performance and durability.
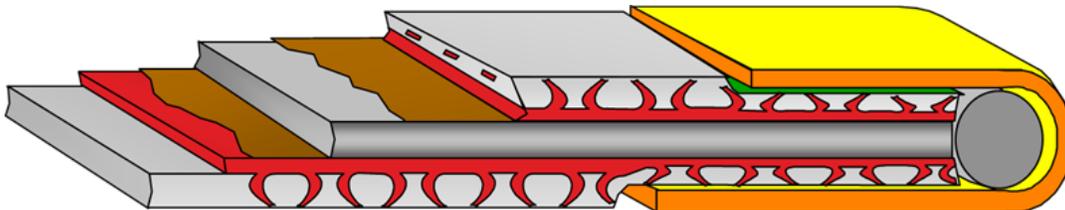
Figure 1. Victocor® Cylinder-Head Gasket Cross-Section

The quality of the adhesive bond is of utmost importance to gasket functionality. The gasket cannot withstand the demanding application conditions, or even be properly manufactured, without a robust bond between layers. Achieving the most durable bond between layers involves

the use of time, temperature, and pressure to effectively cross-link the adhesive. Once these parameters are determined, it must be verified that the manufacturing equipment is capable of providing these conditions in a repeatable and reliable fashion.

2. Manufacturing Process

Heavy-duty cylinder head gaskets are considered large in size with dimensions exceeding 1 meter in length and 0.3 meters in width. The proportions of the gasket require the use of heated presses with correspondingly high surface area to induce the heat transfer under predefined conditions of time, temperature, and pressure. A high volume gasket manufacturer may produce more than 1,000,000 of these gaskets per year. The competitive business environment and practical production limitations require a fast process, on the order of seconds rather than minutes or hours. To process the large sheet materials in a relatively short amount of time, a multi-stage manufacturing process is utilized. The process consists of coils of material being fed into continuous process equipment and automatically bonded in a heated platen press. Process speed requirements dictate that an enormous amount of energy be quickly transferred between the press platen and the gasket material. The gasket material temperature must be increased several hundred degrees Celsius and maintain a precise set point until the cross-linking is sufficient. The variation of the temperature must be kept as low as possible to minimize any deviations in product quality within sheets.
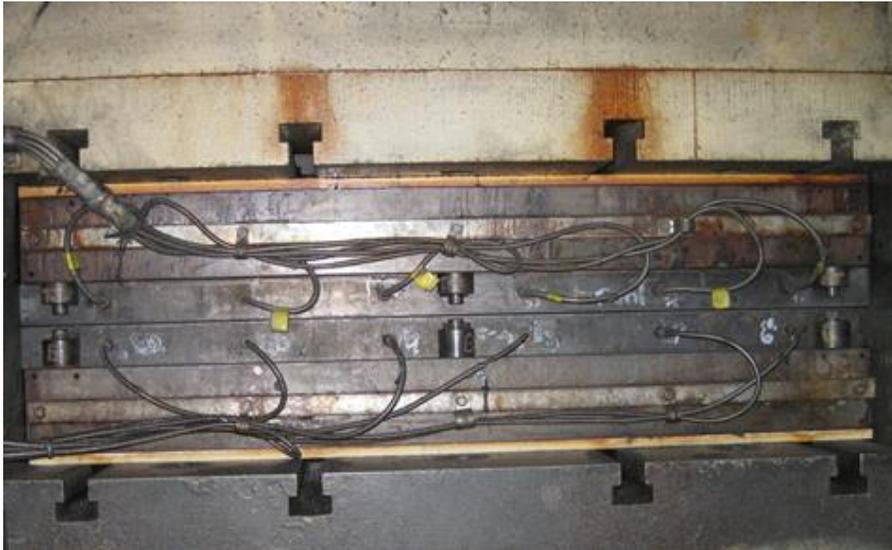
Figure 2. Heated Platen Press.

The design of the heated platens is an ambitious project. Even though there is a wide knowledge base for guidelines involving heated presses, they almost exclusively apply to slower, low-

powered production where fast response and uniformity are of less concern. There are complicated interactions between material and press equipment which are more significant in a fast process. These interactions have severe effects on the resulting process capabilities. The large platens are an expensive item to procure, making upfront design work and simulation critical to the success of the proposed production line. Isight is used to determine the power requirements for the heater cartridges of such a platen system while avoiding potentially costly mistakes.

3.   Simulation Approach

The main goal of the analysis is to determine the minimum power output required by the heater cartridges in order to maintain a nearly uniform set point temperature at the platen surface. The heater cartridges are then sized appropriately for the press. Thermocouples in the lamination platens of the press measure the temperature at set sensor points to ensure a uniform surface temperature. To solve the problem, an iterative procedure using Abaqus is first used to identify the initial power input required to achieve a uniform steady-state temperature on the lamination platens of the press prior to operation. This initial analysis utilizes Abaqus/Standard with custom scripting. The inputs are adjusted for correlation to temperature readouts from the press thermocouples at steady-state operation. Next, an Isight process flow simulates the manufacturing process of coils of material being fed into and automatically bonded in a heated platen press simulated by Abaqus. Using the steady-state temperature map obtained as an initial condition on the press, Isight parameter studies are applied to examine the heater power required to maintain a consistent temperature on the platens in order to minimize both heat loss and press stabilization time during continuous operation. To achieve the objective, the heater cartridge power that will balance a shorter warmup time with a reasonable surface temperature distribution must be determined. If the heater power is too low, the time required to stabilize the system may exceed 1000 seconds, which is not considered acceptable. If the heater cartridge power is too high, the control algorithms will not be able to sustain a low deviation from the set point across the entire platen surface.

3.1   Press Initial Condition Analysis

The first step in the analysis is to calibrate the heated platen press model (shown in Figure 3) to achieve the desired target temperature during steady-state operation. Abaqus/Standard is used to apply surface flux to the heater cartridge locations (shown in Figure 4) in order to achieve the steady-state operation temperature recorded from thermocouple data on the actual press without the gasket in the model. There is no feedback loop modeled in this stage of the analysis; rather, the heat flux is continuously applied until steady-state is reached. The manufacturing process simulation begins once good temperature correlation is achieved.

Press Bed
Bolster Plate
Insulation
Heater Platen
Lamination Platen
Material Sheet

Feed Direction

Lamination Platen
Heater Platen
Insulation
Bolster Plate
Press Bed
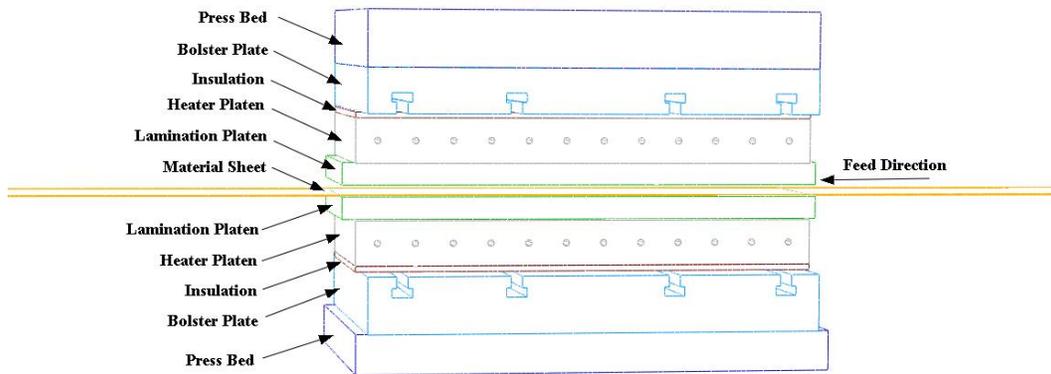
Figure 3. Heated Platen Press Model.

3.2   3-Stage Process with Abaqus and Custom Scripting

The temperature map from the baseline analysis is used as input to the 3-stage heavy-duty cylinder head gasket manufacturing process. The first stage is the material feed, during which the press is open and there is material contact with the bottom lamination platen only. The graphite and steel core are set to the initial condition during this material feed step. The next stage in the process is the press closure. During this step, there is material contact with the top and bottom lamination platens and there is heat transfer across the components. There are two meshed model input files that are changed in the control deck through the use of a control deck included file specification to simulate either an open press or a closed press. The third stage in the process loop consists of the press opening during which the press opens and there is again material contact with the bottom lamination platen only. Throughout all steps of the 3-stage analysis, it is necessary to use a feedback loop. The feedback loop is employed through the use of the Abaqus subroutine UAMP to apply heat flux based on nodal temperatures. There are twelve heater cartridges in the press which are controlled by thermocouple sensors (shown in Figure 4). Each thermocouple sensor controls two heater cartridges.
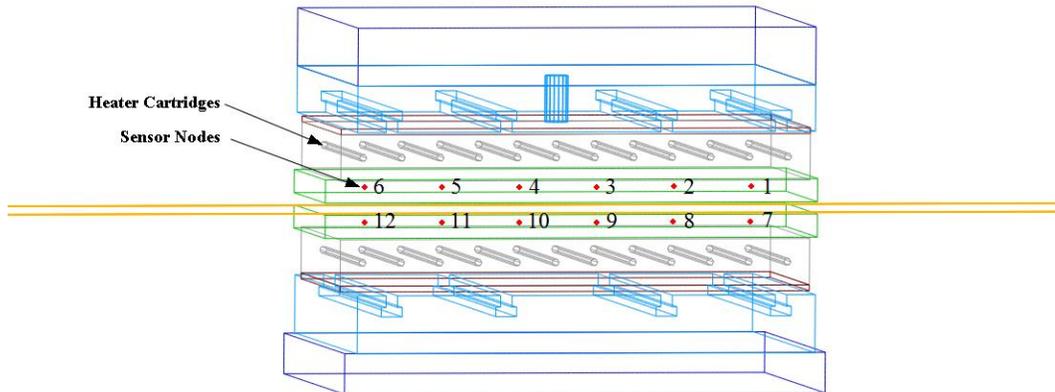
Figure 4. Heater Cartridge and Sensor Node Locations.

The feedback from the sensor nodes using the subroutine UAMP along with custom scripting either turns each pair of heater cartridges off or on separately. Each heater's status depends on the comparison of the temperature at each sensor node to a defined set point temperature. The heaters are turned off or on as needed to maintain a uniform temperature on each platen based on the deviation of each sensor reading from the set point after each time increment. Turning a heater off or on is done by setting the amplitude of the flux applied to that heater to 0 or 1 through the use of the subroutine. Using the temperature map obtained from the initial baseline run as the initial condition on the press, heat transfer analysis is run continuously for 1540 seconds, which amounts to 110 gasket sheets. The temperature on the gasket is reset to the initial condition for each new sheet to simulate new material sheets entering the press. The press temperature is not reset for each new gasket sheet; rather, the temperature condition on the press from the last increment in the preceding step becomes the initial condition of each successive step, thereby simulating continuous operation of the press over time. The input files are generated through the use of a Python submission script and the temperature initial condition in the input file for each successive stage in the process is set through the use of the same Python script. This looping procedure must be repeated each time a new power level is desired to be tested. After the simulation is run, there is also the task of extracting the results and plotting the data. This tedious method of running the model is an ideal candidate for automation.

3.3   3-Stage Process with Isight Implementation

Isight is used to fully automate the heat press heat transfer analysis process (shown in Figure 5) and applied to determine the best heater cartridge power setting to be used by the heat press for manufacturing a given number of gaskets.
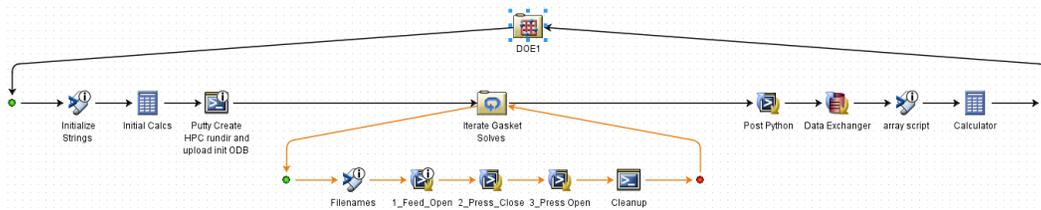
Figure 5. Isight Workflow.

The root of the process, the level with which users are to primarily interact, is configured with the primary input and output parameters needed to drive the process to determine the best power setting. The root level input parameters are:

- *Heater_Cartridge_Power:* the heater cartridge power setting in Watts. This parameter is defined by the user, but is also the primary parameter that is automatically iterated upon using a Design of Experiments (DOE) method.

- *Number_Gasket_Sheets*: the number of gasket sheets to run through the heat press at a given heater cartridge power setting during the manufacturing process.

- *Set_Point*: the desired temperature where all 12 sensors stabilize as the manufacturing process progresses. The best heater cartridge power setting is the one at which all sensor temperatures stabilize in the shortest amount of cumulative time of the simulated manufacturing process.

- *Job_Name*: the Abaqus job name and the name used throughout the process to represent and name the associated content created, such as the runtime directory, output files, etc.

The root level output parameters defined to expose measures that quantify the heat press analysis process results per a given heat press power setting are the following:

- *SetPoint_Aggregate_CT:* the sum of the cumulative time (CT) for each sensor to reach the setpoint temperature after the first initial temperature drop. This parameter assumes that a heater cartridge power setting that achieves the lowest value of this parameter, compared to the others, would be preferred as this represents the heat press achieving an overall steady state in a shorter amount of time than the others.

- *Min_Temp_Over_All_Sensors*: the minimum temperature observed over all sensors throughout the heat press analysis process.

- *Sensor_Slowest_to_Reach_Setpoint*: the sensor number that has the slowest cumulative time to reach the desired set point temperature.

The root level is set to a Design of Experiments component configured to perform a parameter study. This parameter study is configured to modify a single factor, *Heater_Cartridge_Power*. This factor is set at 6 power setting levels: 1500, 2000, 2500, 3000, 3500, and 4000 Watts. This configuration defines an entire multi-gasket heat press analysis process for each *Heater_Cartridge_Power* factor setting. The flexibility of the Isight Design of Experiments component allows the study to evolve in the future as it can be easily expanded and modified to include more parameters at different configurations with different Design of Experiments methods. This can also be easily modified to change from a Design of Experiments method to an Optimization method as desired in the future.

The subflow of the Isight process is the portion of the process that automatically executes all the steps and manages all of the data (both parametric and files) required to complete the simulated heat press manufacturing process for a given number of gasket sheets for each heater cartridge power setting. The steps within the subflow consist of:

- A Calculator component, using the *Heater_Cartridge_Power* parameter within a formula to create the surface flux used on each of the 12 heater cartridges.

- An Operating System (OS) command component, configured with a windows batch file using SSH copy and execution commands, to stage the remote HPC runtime directory that is used throughout the power setting process pass. This staging includes:

  - The creation of a uniquely named HPC runtime directory

  - The transfer of the initial condition Abaqus output database (ODB) file to the HPC runtime directory. This file is referenced to apply the initial temperature of the first Abaqus solve.

  - The transfer of three included files to the HPC runtime directory, which are needed for each of the 3 Abaqus solves per gasket sheet.

- A Loop component (configuration shown in Figure 6) to iterate over the value of the *Number_Gasket_Sheets* parameter. By setting up a parameter for the number of gasket sheets to be solved, the number of iterations is controlled easily from the root components parameters.
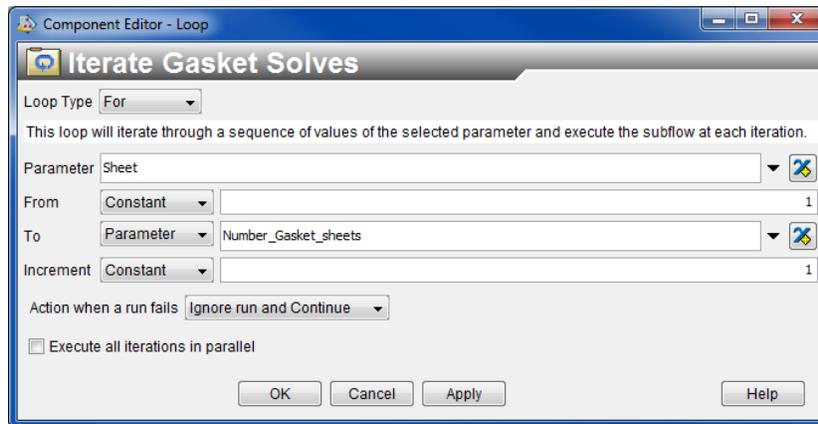
Figure 6. Isight Looping Component.

Within the subflow of the loop component, there are three simulation code components, each configured to create the unique input deck and perform the distributed Abaqus execution for the following stages of each gasket loop pass:

- Abaqus solve 1: material feed

- Abaqus solve 2: press closure

- Abaqus solve 3: press opening

Each of these simulation code components has an input file parse used to create a unique input deck and a windows batch file, changed during runtime, to perform the respective distributed Abaqus execution on a Linux HPC.

The input file parse does two important file parsing actions to the respective Abaqus input deck template to generate a unique input deck:

1) Write the Abaqus output database (ODB) file from the previous Abaqus solve as the current solve's initial temperature reference. If this happens to be the very first Abaqus solve, then the staged initial condition ODB file created from the heated platen press steady-state calibration analysis is used.

2) Replace the value of surface flux (from the calculation) to each of 12 DSFLUX commands within the respective Abaqus input deck template.

Once the input deck is parsed and created, the OS command portion of the respective simulation code component, configured with a windows batch script, is executed to copy the newly created input deck to the HPC runtime working directory. The file is provided as the argument to Abaqus within the distributed working directory.

After the loop is complete, having executed the three Abaqus solves per gasket, an OS command is used to execute a Python script in the runtime directory of the remote HPC to extract the temperature data for each sensor node and place it in a single ASCII file. This single file is parsed with a data exchange component and places the values of the 12 sensor temperatures per cumulative time in Isight resizable arrays. These arrays are passed to a final calculation component configured to create the root level output parameters (*SetPoint_Aggregate_CT, Min_Temp_Over_All_Sensors,* and *Sensor_Slowest_to_Reach_Setpoint*) for each *Heater_Cartridge_Power* factor setting as defined within the root level Design of Experiments parameter study.

4.   Results

Since the heaters are all off at the start of the simulation due to the press being heated to steady-state prior to operation, the temperature immediately drops below the set point as cold material sheets begin to enter the press in operation, thereby causing the heater cartridges to turn on. There is some lag observed for the heat transfer to reach the sensor nodes once the application of heat flux begins after the sensor nodes fall below the set point since the heater cartridge surfaces and sensor nodes are not at the same location. No sensors have stabilized about the set point in 1540 seconds at the 1500 W power setting (shown in Figure 7), while all sensors have stabilized about the set point after 1140 seconds at the 2500 W power setting except sensors 7 and 12 (shown in Figure 8). These two sensors are located at the outside ends of the bottom platen, and are losing the most heat in operation to the outside of the press and the cold gasket sheets entering the press. All sensors have returned to the set point in less than 1000 seconds using the 3500 W power setting for the heater cartridges (shown in Figure 9). Sensor 7 is the slowest sensor to stabilize about the set point at the power settings of interest. Only the 3500 W and 4000 W settings allow sensor 7 to return to the set point in less than 1000 seconds (shown in Figure 10).
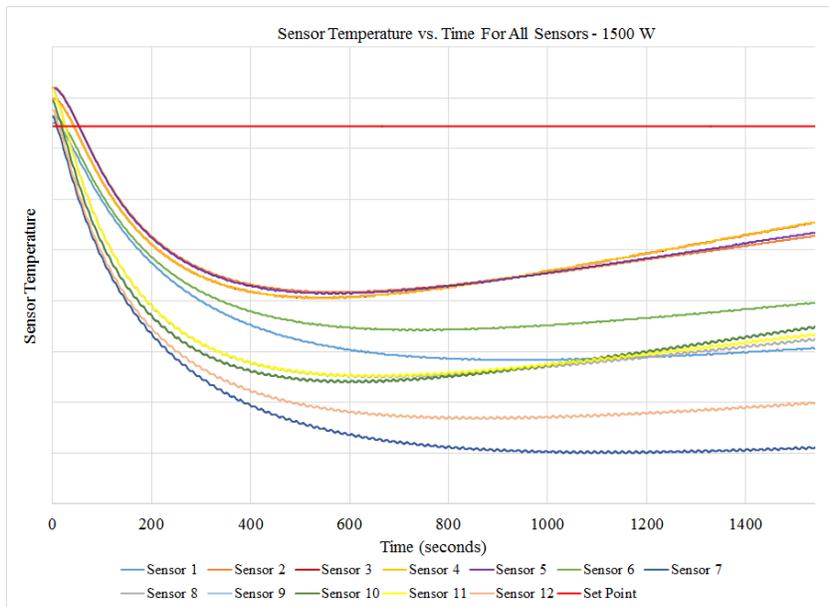
Figure 7. Sensor Temperature Versus Time For All Sensors at 1500W Power.
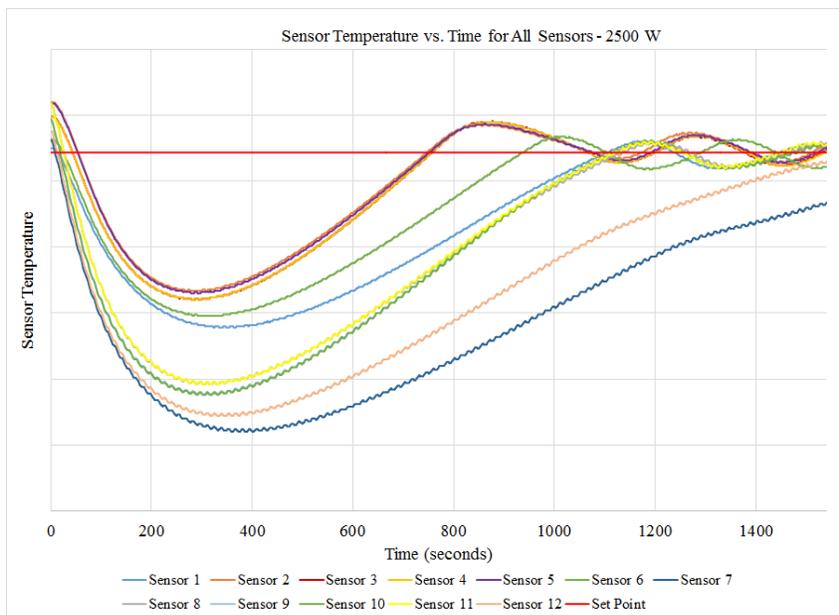
Figure 8. Sensor Temperature Versus Time For All Sensors at 2500W Power.
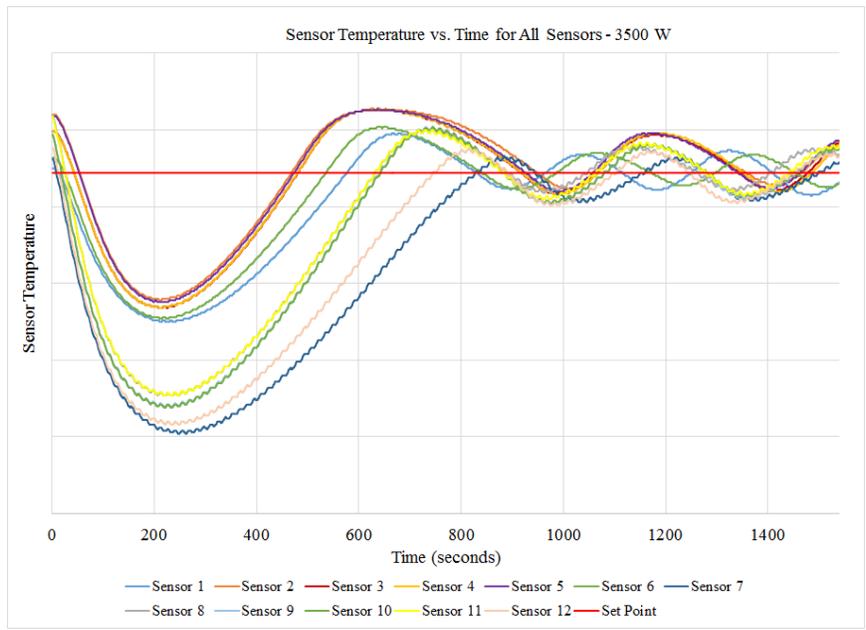
Figure 9. Sensor Temperature Versus Time For All Sensors at 3500W Power.
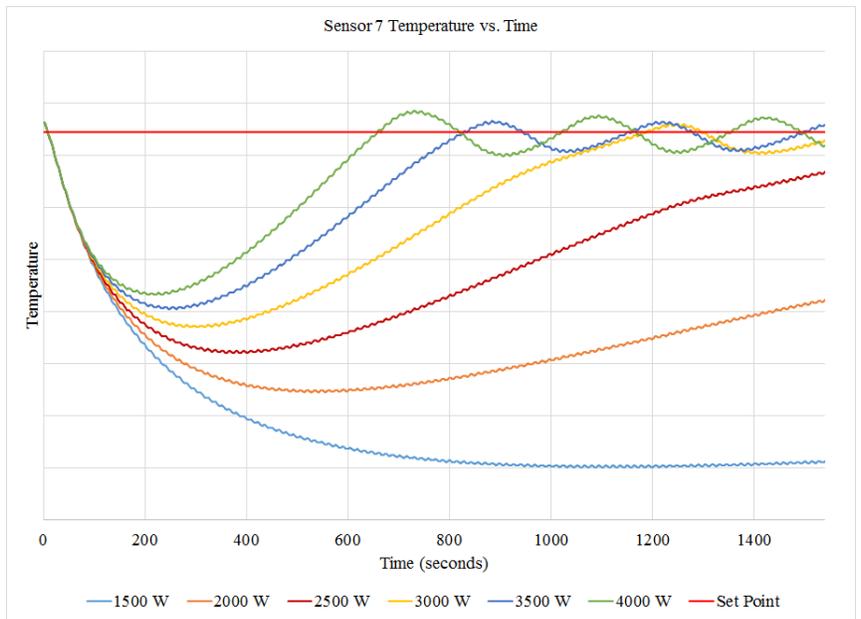
Figure 10. Sensor 7 Temperature Versus Time.

The results of the parameter study are summarized in Table 1. Heater cartridge power less than 3000 W is not sufficient to allow all sensors to return to the set point before 1540 seconds has elapsed. A power setting of 3000 W results in 1190 seconds elapsing before all sensors return to the set point; however, it is desired that less than 1000 seconds elapse before all sensors return to the set point to reduce the scrap rate. Therefore, we see that the minimum heater cartridge power required in order to return all sensors back to the defined set point in less than 1000 seconds while keeping the scrap rate below the desired limit is 3500 W.

Table 1. Results

Heater Cartridge Power (W)	Time for All Sensors to Return to Set Point (s)	Number of Scrap Sheets Before Set Point is Reached	Sensor Slowest to Reach Set Point
1500	> 1540	> 110	1
2000	> 1540	> 110	1
2500	> 1540	> 110	7
3000	1190	85	7
3500	829	60	7
4000	659	48	7

5. Conclusions

The Isight results demonstrate that a cartridge power of 3500 W achieves the desired balance of less than 1000 seconds for system stabilization and minimal surface temperature variation. The uniform surface temperatures improve the quality of the bond in difficult areas near platen edges, eliminating layer delamination and corresponding gasket leakage, thereby creating a more robust gasket. Additionally, the scrap rate experienced in production decreases since the problematic warm up period is reduced. With a working Isight model in place, future work of modifying the lamination platens and the heater platens will be undertaken.