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An Alternative System Identification Method for Friction Stir Processing

Dustin J. Marshall

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

An Alternative System Identification Method for Friction Stir Processing

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Temperature control has been implemented in friction stir processing and has demonstrated the ability to give improved process control. In order to have optimal control of the process, the parameters of the system to be controlled must be accurately identified. The system parameters change with tool geometry and materials, workpiece materials, and temperature. This thesis presents the use of the relay feedback test to determine the system parameters. The relay feedback test is easy to use and promotes system stability during its use. The results from the relay feedback test can be used to determine controller gains for a PID controller. The use of this method, as well as the quality of the resulting control is demonstrated in this paper.

Keywords: friction stir processing, relay feedback test, system identification

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NOMENCLATURE

a	Amplitude of the relay feedback test response
h	Amplitude of the relay feedback test input
Km	Model gain relating system input and output
Ku	Ultimate gain for the relay feedback test
kd	Derivative gain for the PID controller
ki	Integral gain for the PID controller
kp	Proportional gain for the PID controller
ωu	Ultimate frequency related to the ultimate period Pu
Pu	Ultimate period for the relay feedback test
PID	A feedback controller which uses proportional, integral, and derivative components
τ	System time constant
θ	Time delay or dead time
$U(s)$	System or model input
$Y(s)$	System or model output response

CHAPTER 1. INTRODUCTION

1.1 Objective

Friction stir processing is a solid state hot deformation process. It can be used for metal joining, or modifying material properties. The relay feedback test is a system identification method used to determine system models and parameters for a process. The objective of this thesis is to demonstrate the use of the relay feedback test as a system identification method for friction stir processing. It will also demonstrate that the system parameters can be used directly to determine controller gains capable of controlling the process.

1.2 About This Thesis

The body of this thesis consists of a paper being prepared for submission to *The International Journal of Machine Tools and Manufacturing*. It explores the use of the relay feedback test as a system identification method in friction stir processing. This paper demonstrates that friction stir processing tool temperature can be modelled with a First Order Plus Dead Time System, and that the system parameters determined by the relay feedback test are capable of controlling temperature controlled welds in friction stir processing. It explores the use of the relay feedback test over a range of temperatures, studies how well the temperature is controlled at different temperatures, compares how system parameters change with temperature, and tests how the controller gains handle weld disturbances.

CHAPTER 2. THE RELAY FEEDBACK TEST AS A SYSTEM IDENTIFICATION METHOD IN FRICTION STIR PROCESSING

2.1 Abstract

Temperature control has been implemented in friction stir processing and has demonstrated the ability to give improved process control. In order to have optimal control of the process, the parameters of the system must be accurately identified. The system parameters change with tool geometry and materials, workpiece materials, and workpiece holding system. This paper presents the use of the relay feedback test to determine the system parameters describing the friction stir processing system. The relay feedback test is easy to use and promotes system stability during its use. The results from the relay feedback test can be used to determine controller gains for feedback temperature control. The relay feedback test and temperature controlled welds were run in both aluminum and steel. Servo tuned controller gains reduce steady state error to 1-2°C in aluminum, and approximately 3°C in steel. Regulator tuned controller gains eliminate steady state error in both aluminum and steel, but experienced some stability problems when regulator gains determined at higher temperatures were used to control temperature at a lower set point.

2.2 Introduction

Temperature control has been recognized as being beneficial to friction stir processing because the stir zone temperature greatly influences tool life and material properties [1,2]. The ability to control temperature is largely related to correctly determining controller gains; typically the controller gains are based on a system model [3]. Selecting the correct system model and determining the system parameters can be difficult. In friction stir processing, difficulties arise in having accurate system parameters because they change with tool types, weld parameters, workpiece geometry and material being welded [3, 4]. The relay feedback test is a system identification method that works well to determine system parameters while taking less time to run and requiring less material to be used than some other methods. This paper explores the use of the relay feedback test to determine system parameters, and the use of these parameters to calculate controller gains for controlling temperature with and without disturbances.

2.2.1 First Order Plus Dead Time Models

Control models are often used to represent a process, and capture its important dynamics [5]. It is realized that, "all models are wrong, but some are useful [5]." Even though models used may not fit a process perfectly, if the important dynamics are captured, a model may work well enough to design a controller for a system. One model often found in chemical processes is the first order plus dead time (FOPDT) model. A FOPDT is expressed in the time domain as:

$$\tau \frac{dy(t)}{dt} + y(t) = K_m\, u(t-\theta) \tag{2.1}$$

where:

y(t) – process output response
u(t) – process input
K_m – model or process gain
τ – model or process time constant
θ – model or process dead time or time delay

K_m is a gain relating the input action to the output response. τ is the first order time constant, and it describes how long it takes the process to respond to a change in input [5]. θ is a measure of the lag in time before a change in input is recognizable in the output.

2.2.2 PID Controllers

PID controllers are a form of feedback controller, that respond to the error or difference between the set point and output response in a proportional, integral, and derivative manner [6]. The proportional, integral, and derivative action is scaled in intensity based on the proportional (k_p), integral (k_i) and derivative (k_d) gains. All three of the terms are summed together. The action provided by these terms represents the controller output. Ocassionally a bias is summed with the

PID terms to provide the necessary controller action when no error is present [7]. This serves to eliminate unnecessary integrator action. A block diagram for a typical PID controller can be seen in Figure 2.1.

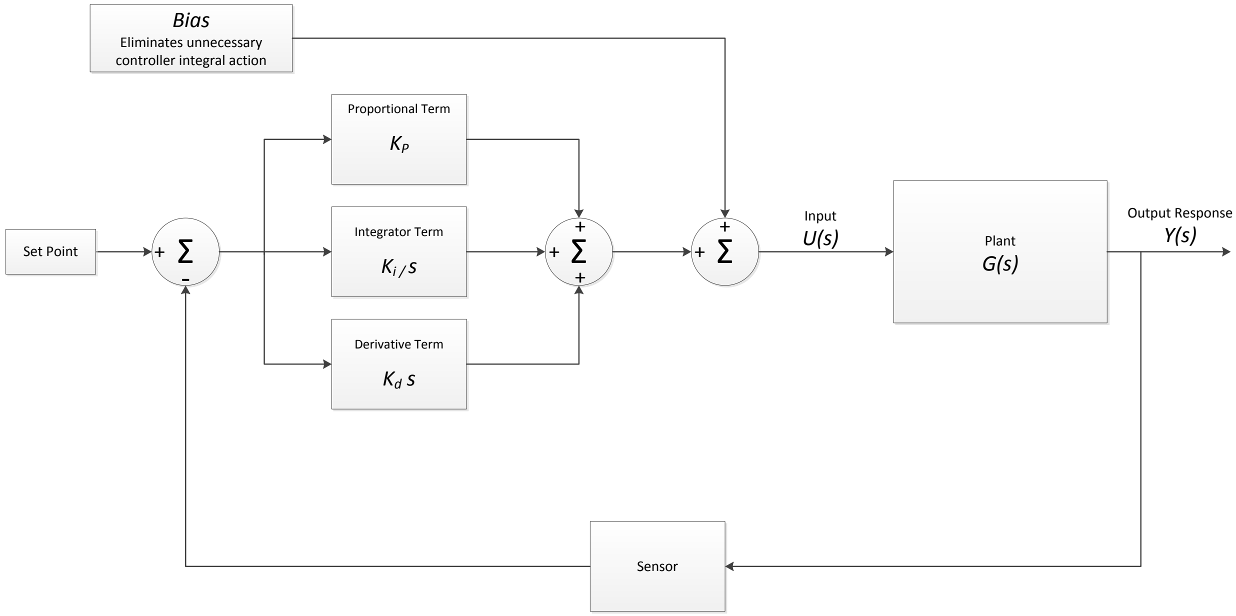

Figure 2.1: A typical block diagram for a PID controller can be seen above.

A PID controller's ability to maintain or control the process response depends on the controller gains being set correctly. These gains vary depending on system type and parameters. The gains also vary depending on the type of desired control, whether the focus is the reduction of steady state error, or the handling of large errors that occur because of set point changes or initial controller activation. Controller gains that focus on reducing small steady state error and the effect of disturbances that cause error are typically classified as regulator gains. Gains that are designed to handle the large errors or set point changes are classified as servo gains [5]. Controller gains are often calculated using tuning rules, which use process models and system parameters to determine the values. A large collection of tuning rules is found in O'Dwyer's "Handbook of PI and PID Controller Tuning Rules" [8].

2.2.3 System Identification

System Identification is the method of using experimental data to fit a model to a process. System identification methods differ primarily in the input signal used to excite the system. Deciding which method to use depends on many different factors relating to the process, such as time to run the process, the cost to run the process, and process stability. All factors must be considered when a method is chosen.

Ziegler-Nichols Step Response

One common method of system identification is the Ziegler-Nichols Step Response Method. This method works by applying a step response to the input value [5]. The system reacts by rising from its initial state to a steady state. A typical step response can be seen in Figure 2.2. From the step response, the parameters for a FOPDT system can be calculated.

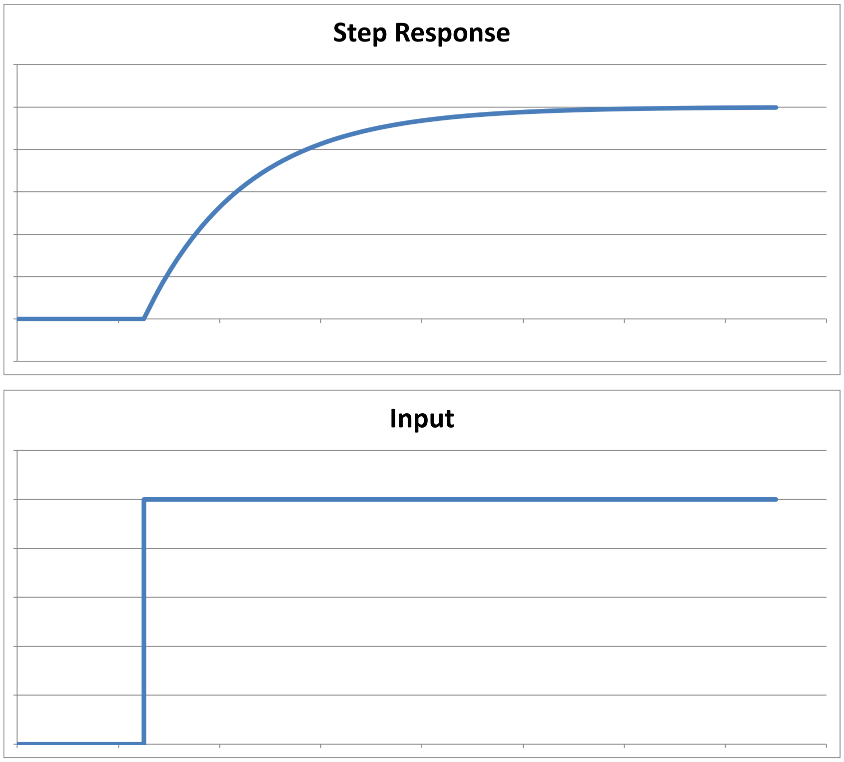

Figure 2.2: The response of a First Order System to a Step Response

Multisine Method

The multisine method is a common frequency response method. The excitation signal to this method is a sine wave with a specified amplitude and frequency. The system is excited with the sine wave, the frequency is changed and the experiment is repeated. The output response is a sine wave with the same frequency, but it has a different amplitude and a phase shift [9]. From the phase and magnitude, bode plots can be made and system models can be determined. For each change in frequency and amplitude an experiment must be run. This method is substantially more time consuming than transient methods [10].

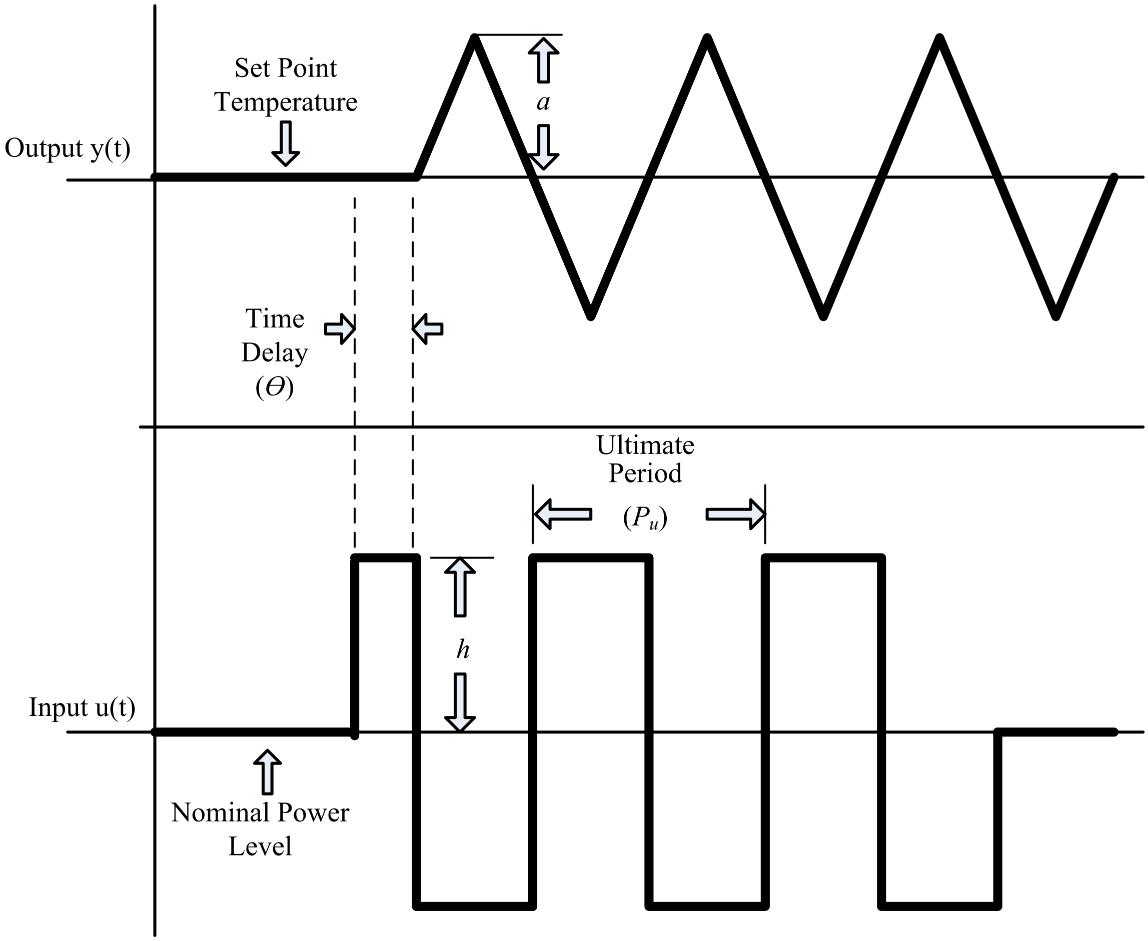

Figure 2.3: The expected system response to a first order plus dead time system with $\theta/\tau \lessapprox .1$

2.2.4 Relay Feedback Test

The relay feedback test is a closed loop system identification method, rather than open loop like the previously described system identification methods [7]. The Relay Feedback test uses a continuous cycle of high and low step responses. The duration and timing of these input responses depends on the feedback about the system output response.

The output response to the excitation input is an oscillating wave. The shape, magnitude, and period of the wave changes depending on the system type and its parameters. A typical input and output signal for a first order plus dead time system with $\frac{\theta}{\tau} \lessapprox 0.1$ can be seen in Figure 2.3. Luyben determined that the shape can be used to determine the system type [11]. He found that sharp discontinuities at the peaks of the output response were indicative of a first order system. Similarly, he found that the smaller the time delay to time constant ratio, the more triangular the waves are as in Figure 2.3. As the time delay to time constant ratio increases, the waves gradually become more square as seen in Figure 2.4.

Yu described some of the advantages of the relay feedback test over other system identification methods such as the step response and the multisine method [7].

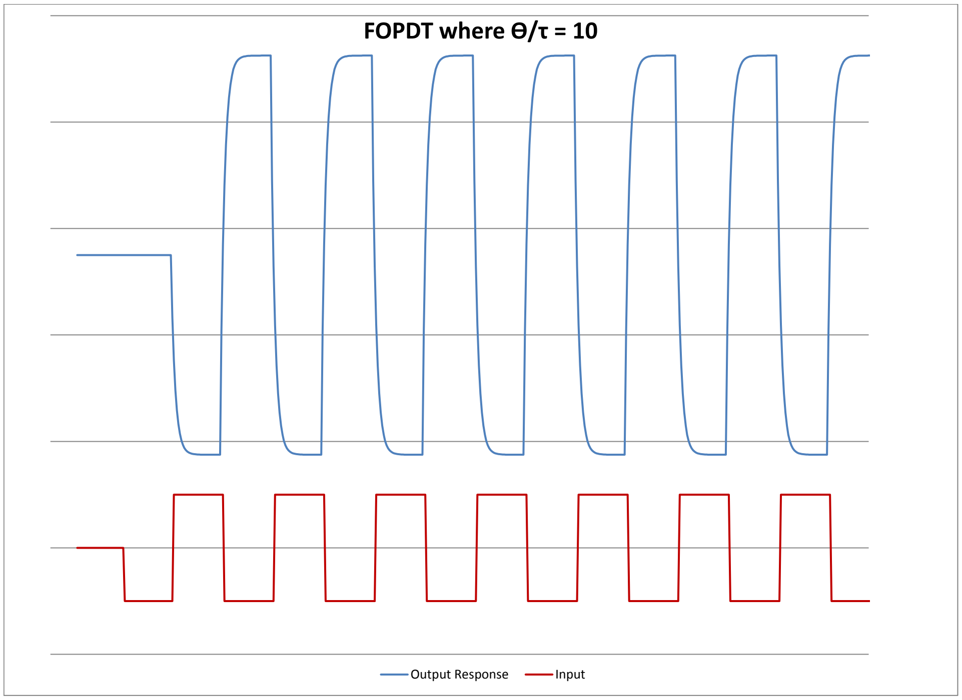

Figure 2.4: The expected system response to a first order plus dead time system with $\theta/\tau \approx 10$

1) The useful process information given by the relay feedback test is close to the ultimate frequency, which is the frequency critical for control.
2) The process is closed loop, which keeps it from being driven away from the nominal operating point.
3) For processes with a long time constant, this method is more efficient than a step or pulse test.
4) The required experimental time is short, as low as two to four cycles of the relay test.

The step response and multisine method both work well for system identification, but there are some inherent difficulties that are more prevalent in systems with a large time delay. One of the main difficulties that the step response method and the multisine method experience is the amount of time required to obtain data for one system. The relay feedback test is a good system identification method for friction stir processing, because it requires minimal time or material. A single step test requires a minimum of 3-5 τ to be run. If the relay feedback test is run for the recommended 4 cycles, it only needs to be run for 16 θ or 1.6 τ which is significantly shorter. The relay feedback test has multiple cycles, from each cycle the system parameters could be calculated, but having multiple cycles provides an average of the parameters. This helps to ensure that the actual system parameters agree with the calculated values, and allows for statistical comparison. The step test only provides one set of parameters, and must be run multiple times to ensure that the system parameters are correct. The multisine method requires dramatically more material than either of the other methods because it must be run at multiple frequencies. Additionally, both the sinusoid and step response methods are open loop, which can allow the process to become unstable. The difficulties experienced with the step response and multisine methods are both overcome with the relay feedback test. The closed loop nature of this method helps ensure stability, and the relay feedback test only needs to cycle between two and four times. This means the welds are relatively short when compared to the step response method, and only one weld needs to be run in order to determine a system; thus requiring much less time and material to run than the step response and sinusoid frequency response methods.

2.2.5 Calculating FOPDT Parameters from Relay Feedback Test Results

The system parameters for a first order plus dead time system can be calculated from the relay feedback test [7]. The first thing that must be calculated is the frequency response of the system, including the ultimate gain (K_u) and the ultimate frequency (ω_u). The ultimate gain is calculated from the amplitudes of the input and output signals:

$$K_u = \frac{4h}{\pi a} \tag{2.2}$$

where a is the amplitude of the output and h is the amplitude of the input as seen in Figure 2.3. The ultimate frequency is calculated from the ultimate period (P_u) as:

$$\omega_u = \frac{2\pi}{P_u} \tag{2.3}$$

The ultimate period is simply the period of either the input signal or output response. The model gain K_m represents how the output of a system changes in response to a change in the input, and can be calculated as:

$$K_m = \frac{\int y(t)dt}{\int u(t)dt} \tag{2.4}$$

Once K_m is known, τ can be calculated as:

$$\tau = \frac{\sqrt{(K_m\, K_u)^2 - 1}}{\omega_u} \tag{2.5}$$

When the time delay to time constant ratio is 0.1 or less,

$$\theta = \frac{P_u}{4} \tag{2.6}$$

2.2.6 Temperature Control in Friction Stir Processing

Three notable groups have done work to implement temperature control in friction stir welding; these include Cederqvist, Fehrenbacher *et al.*, and Ross *et al.* All three groups have worked to implement temperature control to the friction stir welding process. Cederqvist used a complex cascaded loop controller to adjust tool temperature [1]. Fehrenbacher *et al.* used a compensator controller design to adjust the spindle speed to maintain temperature [4]. Ross *et al.* used a PID controller that adjusted the spindle power [3]. A recursive algorithm embedded in the control loop commanded a spindle torque based on the current spindle speed to achieve the desired power. This recursive algorithm was used to adjust torque because there was no direct method to control power.

Fehrenbacher and Ross both discussed the use of system identification to determine system models and parameters. They both found that friction stir processing could be modelled by a FOPDT model [3, 4]. Fehrenbacher used the multisine frequency method, and Ross used the Ziegler-Nichols step response method. After finding system parameters, Fehrenbacher used some frequency response methods to design a compensator controller. Ross used tuning rules to determine controller gains for welds run in both aluminum and steel [3].

This paper demonstrates that the relay feedback test can be used to determine system parameters in one short weld. These parameters will then be used to control weld temperature. The paper also demonstrates that these parameters are capable of handling mild disturbances, and may be used for a variety of temperatures.

2.3 Equipment And Experimental Setup

All welds were run on a purpose built friction stir welding machine. It is a model RM-2 built by TTI. Temperature controlled welds were run using a PID controller based on the work of Ross [3]. This PID controller differs from Ross's because the derivative term is part of the feedback path rather than the forward path [10]. The PID controller is a type of non-interacting parallel form controller. It can be expressed as:

$$u(t) = Bias + k_p\, e(t) + k_i \int e(t)\ dt + k_d\, \frac{d\left(T_{\text{tool}}(t)\right)}{dt} \tag{2.7}$$

Where:

Bias - provides the necessary controller action for the initial conditions assuming no error is present

e(t) - is the error or difference between the measured tool temperature and the set point temperature

$T_{tool}(t)$ - is the current tool temperature

k_p,k_i,k_d - are the PID controller gains

All welds used ASTM A-36 hot rolled steel as backing plate material. The thermocouples used to measure tool temperature were K type with a diameter of 0.032 inches. Aluminum welds were run in 0.25 inch thick 7075-T6 aluminum. The plates where lightly wiped to remove oil before processing, but no surface oxidation was removed. Steel welds were run in 0.25 inch thick 1018 cold rolled steel. These plates were wiped with methyl alcohol prior to processing. All welds were run with a feed rate of 6 IPM unless otherwise specified.

Aluminum welds were run with a CS4 tool made from H13 steel. This tool has a pin angle of 32.5°, a pin length of 0.2 inches and a shoulder diameter of 0.98 inches [3] [12]. The thermocouple was located 0.06 inches from the end of the pin as seen in the Appendix in Figure A.1. This tool was run with a plunge depth of 0.24 inches.

The relay feedback test and temperature controlled welds in steel were run with two different PCBN tools. The first tool was used for the first two relay welds, and then the temperature controlled welds. The second was used for another relay weld, and then two temperature controlled disturbance welds. Both of the tools used were E44111 PCBN tool produced by MegaStir Technologies. They differed in the depth of thermocouple hole. The first had a hole depth of 0.842 inches. The second had a hole depth of 0.667 inches. This tool can be seen in the Appendix in Figure A.2. This tool was plunged to a depth of 0.202 inches

2.4 Aluminum Relay and Temperature Controlled Welds

2.4.1 Methods

Relay

An additional subroutine was added to the friction stir welding machine's PLC to allow the relay feedback test to be performed. This routine captured the current tool temperature and power level when the relay feedback test started. These were stored as a set point temperature and nominal power level. The high and lower power settings used in the relay test were calculated from the nominal power level. The low level was 90% of the nominal level, and the high power setting was 110% of the nominal power level. As soon as the tool temperature moved above or below the set point temperature, lower or higher power setting was applied. The oscillations continued until the end of the weld, and a tool extraction process was started.

A total of 9 relay welds were run in aluminum. Three welds were run at 425°C, three were run at 450°C, and the final three at 475°C. These welds were 18 inches in length. The first six inches of the weld were spindle speed controlled. During the first 6 inches the feed rate and spindle speed could be varied to bring the tool temperature up to the desired value before the relay section started. Attempts were made to have the tool temperature steady for at least 2 inches before the relay feedback test started. The last 6 inches were the relay feedback test. During the relay feedback test, a steady feed rate of 6 IPM was used.

Temperature Controlled Welds

The system parameters were used to calculate the PID gains. Due to some minor asymmetry observed in the amount of time the power level was set high compared with low during the relay weld, *a* was calculated for both heating and cooling. The only parameter affected by this is τ. It was decided that the numerically smaller τ value of the two would be used. The reason for this is that the numerically smaller or faster τ results in slower responding PID gains which promote stability. The τ values seen in Table 2.1 and Table 2.5 are the faster or numerically smaller values.

The PID gains were calculated from the system parameters using tuning rules. A tuning rule was chosen that is designed to reject disturbances (regulator), and another that is used for set point tracking (servo). The regulator tuning rule chosen is Murrill's minimum integrated time absolute error (ITAE) tuning rule because this was the rule originally used for disturbance rejection by Ross [3]. The servo tuning rule is Chen's 0% overshoot rule. These rules can be found in O'Dwyer's [8], "Handbook of PI and PID Controller Tuning Rules."

Murrill's minimum ITAE tuning rule calculates PID gains as follows:

$$k_p = \frac{1.357}{K_m}(\frac{\tau}{\theta})^{0.947} \tag{2.8}$$

$$k_i = k_p \frac{0.842}{\tau}(\frac{\theta}{\tau})^{0.738} \tag{2.9}$$

$$k_d = 0.381 k_p \tau (\frac{\tau}{\theta})^{0.995} \tag{2.10}$$

Similarly, Chen's 0% Overshoot Rules uses the following equations to calculate the PID gains.

$$k_p = \frac{0.6\tau}{K_m \theta} \tag{2.11}$$

$$k_i = \frac{kp}{\tau} \tag{2.12}$$

$$k_d = 0.5 k_p \theta \tag{2.13}$$

Two temperature controlled welds were run for each of the relay welds. The first used the servo gains, and the second the regulator gains. The set point temperature of the welds was set to either 425°C, 450°C, or 475°C rather than the temperature the relay was actually run at, since the relay weld was attempting to find a system for those set points in the first place. These temperature controlled welds were fourteen inches in length. The first four inches of the weld was a constant spindle speed section to allow the tool temperature to approach the set point temperature. After four inches, the PID controller was engaged. The PID controller made adjustments to the spindle power to reduce error in the temperature.

2.4.2 Results

Relay Feedback Test

Relay welds were run in aluminum. Figure 2.5 shows a relay welds run at 425°C. These results are typical for the relay welds run in aluminum. All 9 relay weld plots are listed in the appendix.

System parameters were calculated from the relay welds. These can be seen in Table 2.1. These system parameters have been compared with temperature in Figure 2.6. It can be seen that the model or process gain, K_m decreases with increasing temperature. The system time constant (τ) increases with temperature. The time delay (θ) isn't dramatically affected by temperature.

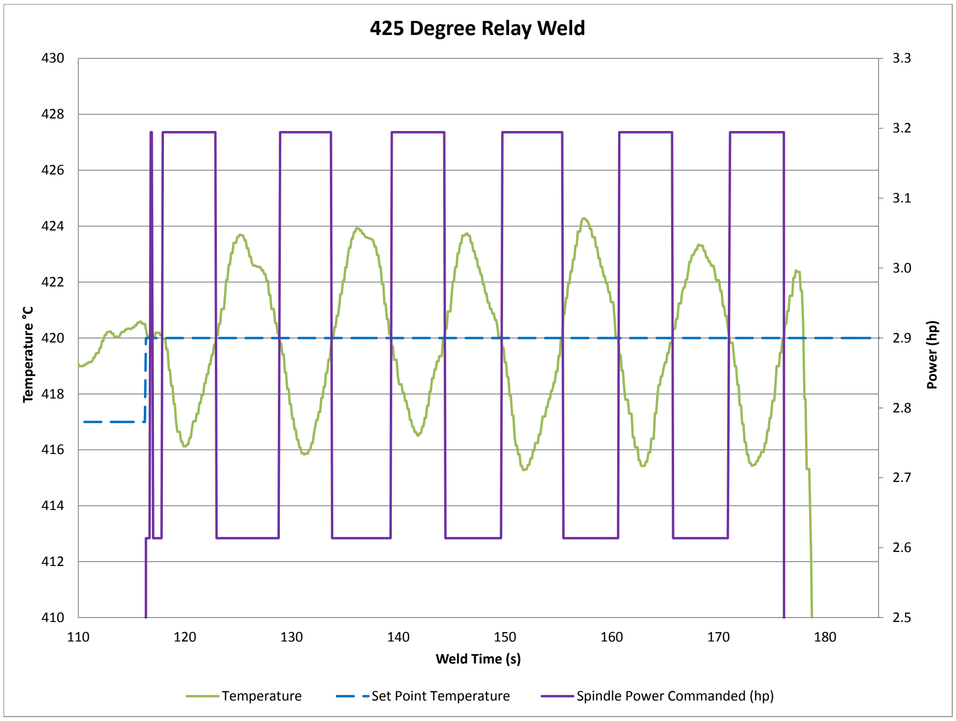

Figure 2.5: A relay feedback test run at 425°C in aluminum. This relay weld is typical example of an aluminum relay weld.

The relay results demonstrate that the spindle power to tool temperature can be modeled as a first order plus dead time system as was observed by both Fehrenbacher and Ross. This can be seen in the fact that the oscillations of the relay reach full amplitude on the first cycle. The peaks

Table 2.1: The system parameters that were calculated for the nine relay welds run at 425, 450, and 475°C.

Weld	Set Point Temperature (°C)	K_m (°C/hp)	τ (s)	θ (s)
425 Relay 1	426	143.53	23.7	2.77
425 Relay 2	421	139.72	18.5	2.51
425 Relay 3	420	143.78	21.2	2.67
450 Relay 1	451	139.91	42.4	2.48
450 Relay 2	455	134.43	39.8	2.57
450 Relay 3	459	129.83	36.8	2.45
475 Relay 1	476	134.63	56.3	3.22
475 Relay 2	470	129.11	54.2	2.75
475 Relay 3	482	132.98	61.0	2.81

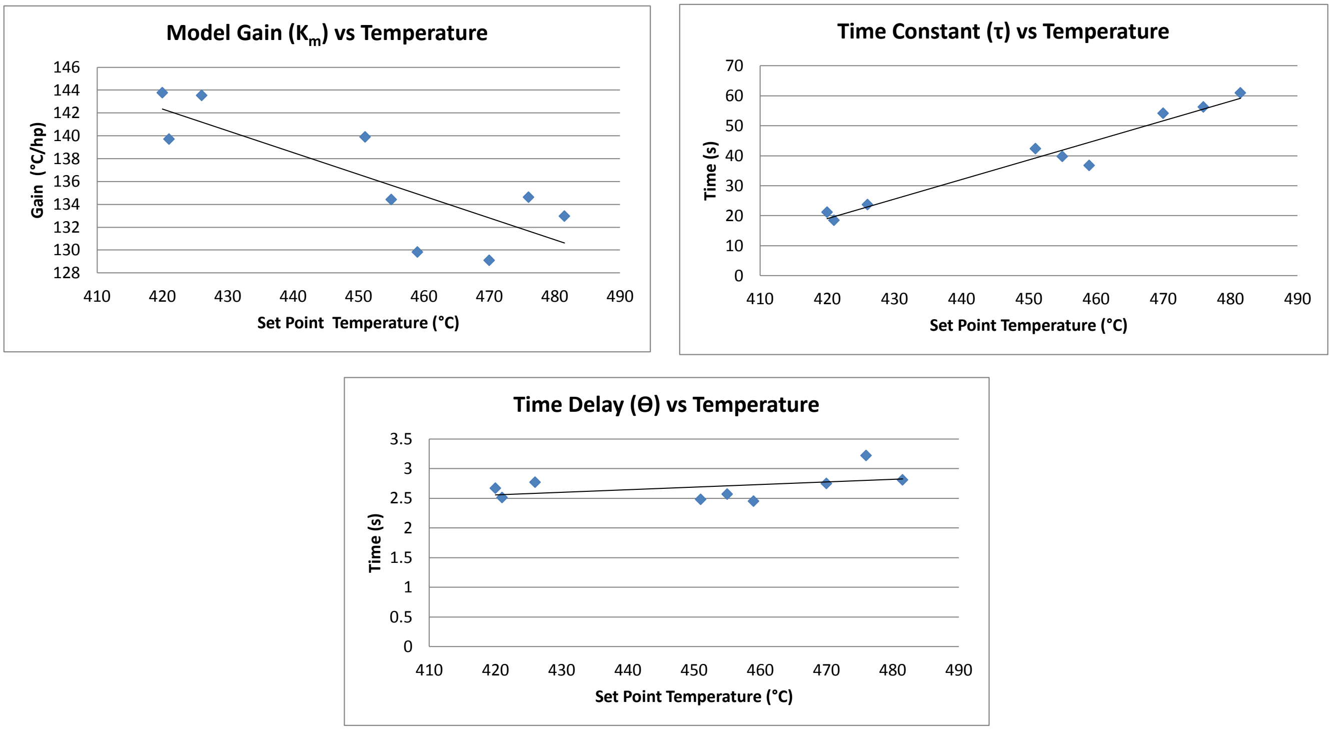

Figure 2.6: System Parameters as a function of set point temperature.

are sharp, and the shape of the oscillations are indicative of a first order system with time delay, which has a time delay to time constant ratio of approximately 0.1.

Aluminum Temperature Controlled Welds Using Servo Gains

Temperature controlled welds were run using the servo gains calculated from the system parameters found in Table 2.1. One temperature controlled weld was run for each of the nine relay welds. Figure 2.7 depicts the three temperature controlled welds run at 450°C using servo gains.

It can be seen that the temperature is very close to the 450°C set point temperature, but there is steady state error throughout most of the weld. These results are typical for all the servo welds, with only minor differences in the initial error, peak temperature, and the settling time. The settling time was calculated for 2°C. The initial error, peak temperature, settling time and steady state error for all nine servo welds can be seen in Table 2.2. The steady state error in the table was calculated at the end of the weld. It can be seen that all but one weld still had steady state error by the end of the weld.

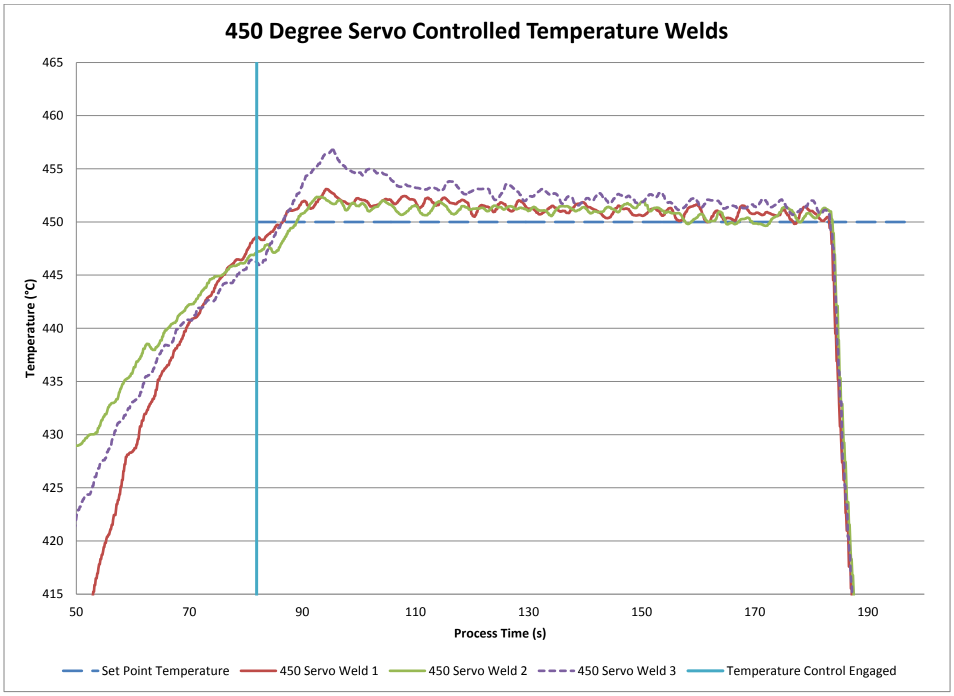

Figure 2.7: Three 450°C welds were run using servo gains for the PID controller. These welds are typical servo welds.

Aluminum Temperature Controlled Welds Using Regulator Gains

The welds run with regulator gains are similar to those run with servo gains. One weld was run for each of the nine relay welds. Figure 2.8 depicts the three temperature controlled welds run at 450°C with the regulator gains.

Table 2.2: The initial error, overshoot, and settling time for the temperature controlled welds using the servo gains.

Weld	Initial Error (°C)	Overshoot (°C)	Settling Time (s)	Steady State Error (°C)
425 Weld 1	1.59	5.40	51.67	-0.5
425 Weld 2	0.21	3.81	22.23	0
425 Weld 3	-8.54	3.49	26.46	0.75
450 Weld 1	-1.43	3.10	17.42	0.75
450 Weld 2	-2.84	2.53	14.33	0.5
450 Weld 3	-3.86	6.78	54.46	1.5
475 Weld 1	-4.63	2.23	15.52	0.65
475 Weld 2	-8.57	5.76	53.33	0.75
475 Weld 3	-6.04	5.92	41.36	1.75

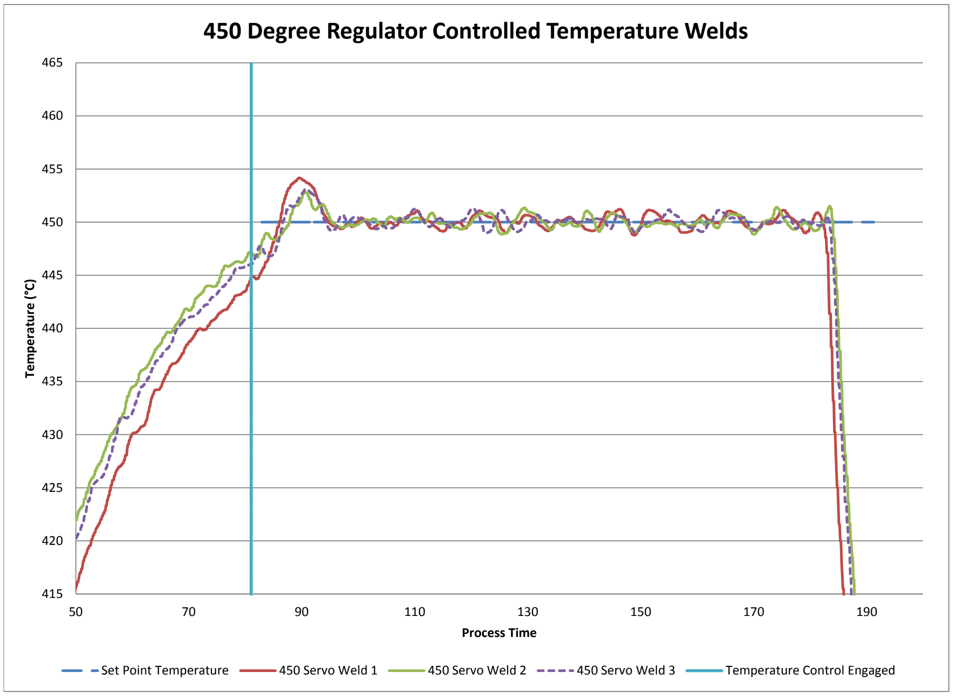

Figure 2.8: This figure shows the three 450°C welds, run using regulator gains for the PID controller. These welds are typical regulator welds.

The results seen in Figure 2.8 are typical for the temperature controlled welds run using regulator gains. Temperature is very well controlled with no steady state error and a fast settling time. All of the other welds were similar. The plots for 425°C and 475°C welds can be viewed in the appendix. The results for all 9 regulator welds are summarized in Table 2.3.

Table 2.3: The initial error, overshoot, and settling time for the temperature controlled welds using the regulator gains.

Weld	Initial Error (°C)	Overshoot (°C)	Settling Time (s)	Steady State Error (°C)
425 weld 1	-6.69	7.60	13.75	0
425 weld 2	-3.50	4.57	13.44	0
425 weld 3	2.17	2.95	3.09	0
450 Weld 1	-5.10	4.16	11.88	0
450 Weld 2	-2.96	2.82	9.35	0
450 Weld 3	-2.46	3.12	9.12	0
475 Weld 1	-12.47	7.67	18.45	0
475 Weld 2	-7.40	6.77	16.33	0
475 Weld 3	-8.34	5.61	16.46	0

2.4.3 Relay Weld Discussion Aluminum

Short Cycles

Short cycles are occasionally seen in the relay welds. Figure 2.5 has one of these cycles at 118 seconds. These occur because of fluctuations in the temperature signal near the set point temperature. The reason for this occurring is unknown. It is believed that this may be related to the noise in the signal, but it is possible that another underlying factor could be causing it to occur.

Non-Linearities

It can be seen that Figure 2.5 does not exactly match the typical FOPDT system with a time delay to time constant ratio of 0.1 or less. With increasing temperature, the aluminum relay welds tend to have minor oscillation in temperature near the peaks as seen in the first and second heating peaks from Figure 2.5.

Asymmetry

Occasionally, there is a difference between the time that the relay feedback test spends with the power level set to high versus set to low. Typically, when this was observed, more time was spent with the power set to a low power level, than a high power level. This was observed in most, but not all of the relay welds, and will be seen later in Figure 2.9. Yu characterized this asymmetry as a load disturbance that can be corrected by using an asymmetric input signal where the high and low power settings use different percentages [7]. It is unclear what caused this asymmetry. One possible explanation is that this asymmetry is caused by a set point temperature, and a nominal power level that do not match each other. If the temperature or power level were to change because of noise or some other factor, a mismatch would cause asymmetry to occur.

Another possible explanation is that it could actually be related to the heating and cooling that occurs. It could be that it is possible to add or remove heat more quickly causing an asymmetry to show up. Typically, the relay welds spent less time at the high power level. This would occur if it was possible to heat the system quicker than heat was being remove at low power levels. This asymmetry can be seen in many of the relay feedback test welds in the Appendix.

Table 2.4: The error in τ based on using a for heating or cooling rather than a average

Weld	Relative Error in τ
425 Al Relay Weld 1	18%
425 Al Relay Weld 2	18%
425 Al Relay Weld 3	4%
450 Al Relay Weld 1	6%
450 Al Relay Weld 2	34%
450 Al Relay Weld 3	21%
475 Al Relay Weld 1	22%
475 Al Relay Weld 2	12%
475 Al Relay Weld 3	16%

The asymmetry seen in the welds was quantified, by comparing the difference between the a value originally calculated for either heating or cooling with an average of the two. It can be seen that if the average a value was used over a calculated for either heating or cooling, τ would have differed by the amount shown in Table 2.4.

Repeatability of System Parameters After A Tool Change

It has been observed that system parameters tend to change when tools are changed. The difficulty is that when removing and reinstalling the tool, which involves the removal and installation of the thermocouple, the system seems to experience some change in value.

The temperature is more consistent from weld to weld when the tool is not removed between welds. A method for improving temperature repeatability between tool changes should be developed.

2.5 Steel Welds

2.5.1 Methods

Relay

Initially two relay welds were run in steel, but a third was run when the PCBN tool experienced a pin failure during a disturbance weld. The relay welds for the first tool were run at 730°C and 800°C. After switching tools, another relay weld was run at 800°C. The tools used in both sets of relay welds were E44111 as mentioned in the equipment section, but the thermocouple hole had a different depth, which affected the system parameters. These welds were 22 inches in length. The first 10 inches were spindle speed controlled; during that section, the feed rate and spindle speed were varied as needed to reach and maintain the desired temperature. The steel welds also used a ±10% adjustment to power.

Temperature Controlled Welds

A temperature controlled weld was run at 730°C and another at 800°C, corresponding with the first two relay welds run. The temperature controlled welds run were 22 inches in length. The first inch was a feed ramp from 0 IPM to 6 IPM at a constant spindle speed. The next 5 inches were a constant feed rate and constant spindle speed section, that allowed the tool to get up to temperature. The last 16 inches of the weld were temperature controlled; the first 9 inches of the temperature controlled portion used servo gains, and the remaining 7 inches of the weld used regulator gains to control the temperature. The servo gains were used in conjunction with the

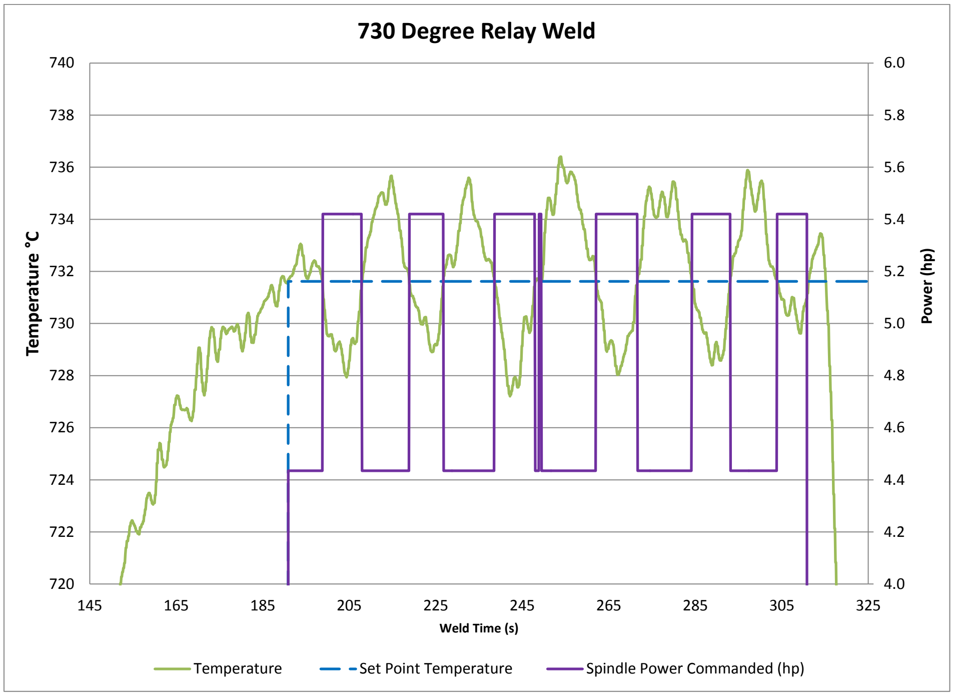

Figure 2.9: Temperature and power for a relay weld in steel.

regulator gains to reduce the risk of having a large initial error in temperature causing tool failure through overshoot or other instabilities.

2.5.2 Results

Relay

The 730°C relay weld can be seen in Figure 2.9. The system parameters for the relay welds run in steel are summarized in Table 2.5.

Table 2.5: System parameters for the three relay welds in steel.

Weld	Set Point Temperature (°C)	K_m (°C/hp)	τ (s)	θ (s)
1-7-0001	732	150.46	74.3	5.19
1-7-0002	802	144.34	102.9	7.82
1-10-0003	789	132.76	89.2	5.56

Temperature Controlled Welds

Temperature controlled welds were run with the first PCBN tool. Rather than run one weld to test servo gains and another to test the regulator gains, each temperature weld had a section of temperature control using servo gains, followed by a section using regulator gains. The first weld was run at 720°C. The next was run at 800°C. These welds can be seen in Figure 2.10. It can be seen that both welds have significant steady state error for the servo section. The 720°C weld has between about 3-5°C steady state error, and the 800°C weld has about 2.5°C steady state error throughout the servo section of the weld. After switching to regulator control, the controller worked to eliminate the steady state error. By the end of both welds, the steady state error had been eliminated.

2.5.3 Relay Weld Discussion Steel

Short cycles, asymmetry and non-linearities were all seen in steel as they were in aluminum. The steel seems to have more steady oscillations through out the whole cycle, which are

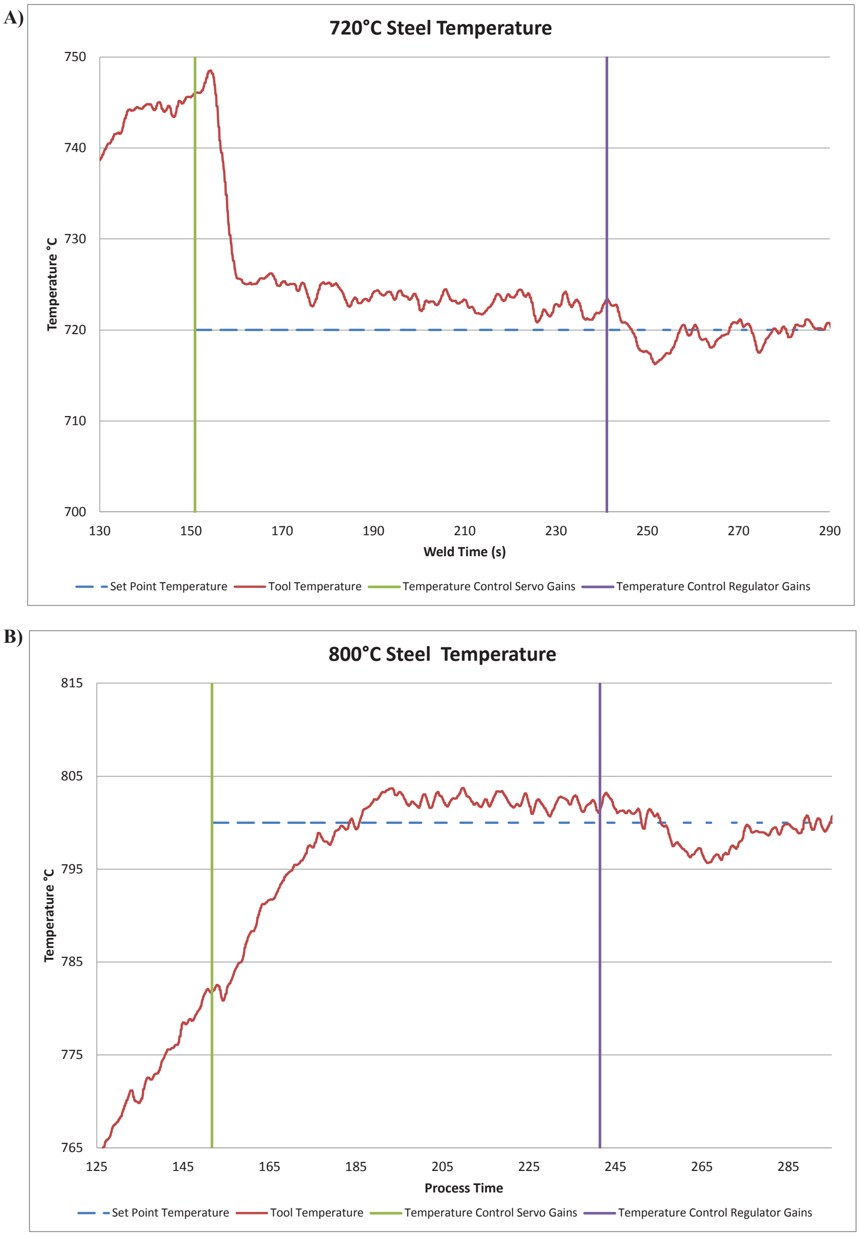

Figure 2.10: Two temperature controlled welds were run in steel. A) was run at 720°C and B) was run at 800°C. Both used servo gains at the beginning and regulator gains at the end of the temperature controlled section

also larger. The reason for the increased non-linearities is unknown. As with the aluminum welds, an error was calculated showing how τ would have differed if a average was used over a heating or cooling. Table 2.6 summarizes these results.

Table 2.6: The error in using *a* for heating or cooling compared with *a* average in steel.

Weld	Relative Error in τ
730 Steel Weld	9%
800 Steel Relay	2%
800 New Tool	28%

2.6 PID Gain Temperature Sensitivity Tests

2.6.1 Methods

After the initial set of temperature controlled welds, a set of twelve aluminum welds was run to study how well the gains from one temperature applied to another. For this test, both regulator and servo PID gains were used. At each temperature, the system time constants (τ) were compared, and the PID gains for the system with the median τ value were chosen. These gains were then used to control temperature welds at the two temperatures which weren't their set points.

When a weld was run at some set point temperature, the regulator and servo gains from the two non- set point temperatures were applied to test their ability to control temperature. An example of this is the four 425°C temperature welds. These welds were running using the 425°C set point, but the gains used were the 450°C regulator and servo gains, and the 475°C regulator and servo gains. These welds were set up the same as the other temperature controlled welds, where the first four inches were a constant spindle speed section, followed by a 10 inch temperature controlled section.

2.6.2 Results

The welds run with the servo PID gains look similar to the temperature welds previously run with those gains. There are no large differences between the three sets of temperature controlled welds using the servo gains; one exception to this is that the 475°C temperature controlled welds using the 425°C and 450°C gains have a longer settling time than the gains for that temperature. The results of these welds can be seen in Figure 2.11.

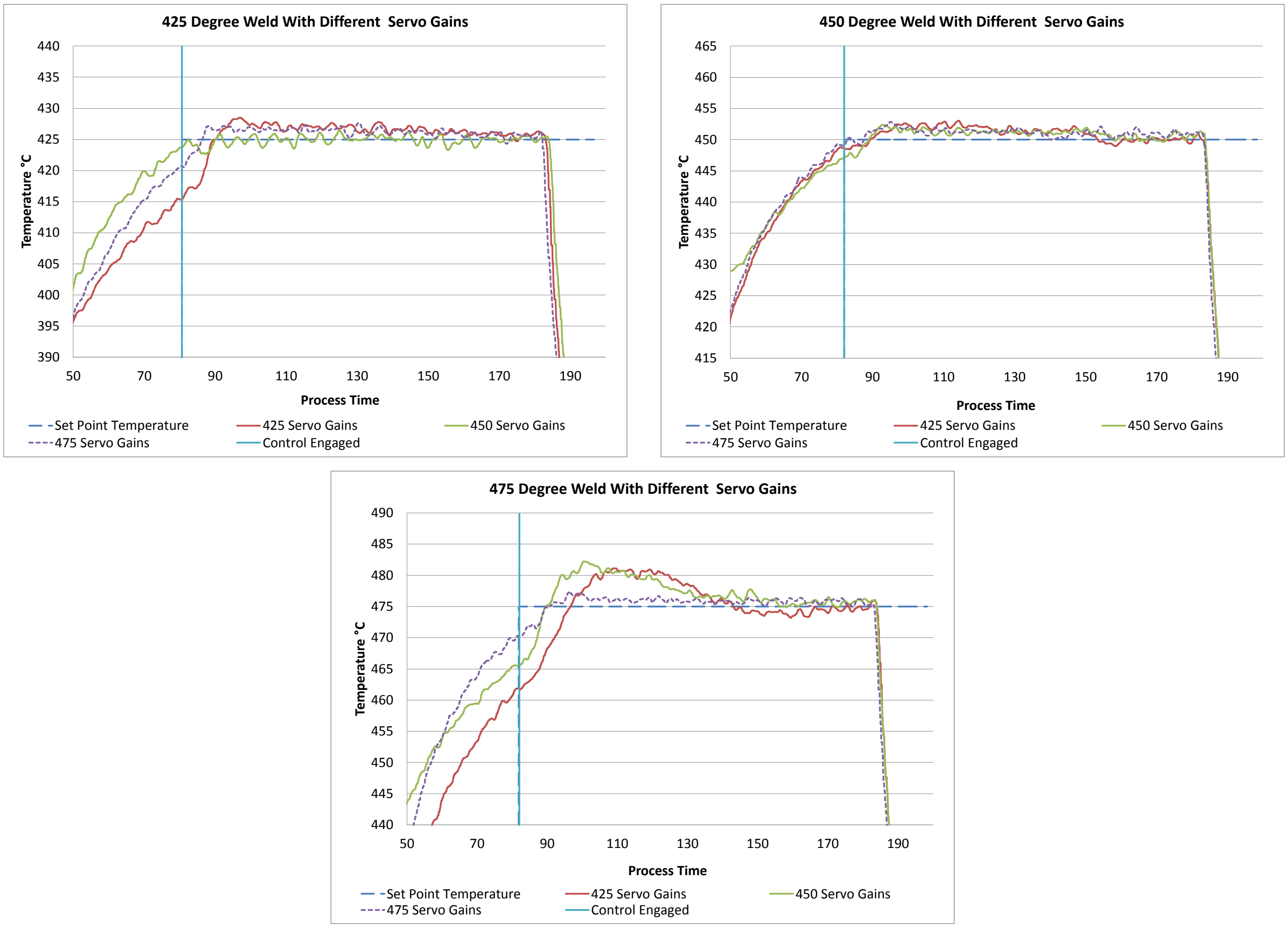

Figure 2.11: The servo gains from the 425°C, 450°C and 475°C aluminum temperature controlled welds were used to control temperature at set points other than their own.

The regulator gains are much more temperature sensitive than the servo style. It can be seen in the 425°C plot of Figure 2.12 that the 450°C regulator gains caused the weld to be marginally stable and the 475°C gains caused it to be unstable. The 450°C regulator weld looks like the 450°C regulator welds run with the gains for that temperature. The 475°C was controlled well by all of the gains, but it was observed that the 425°C had a longer settling time than the other gains.

2.6.3 Discussion

It has been observed that the gains are temperature dependent. The gains from the higher temperatures are more aggressive than those from the lower temperatures. When the gains from higher temperatures are used to run welds at lower temperatures, it can result in the welds run at

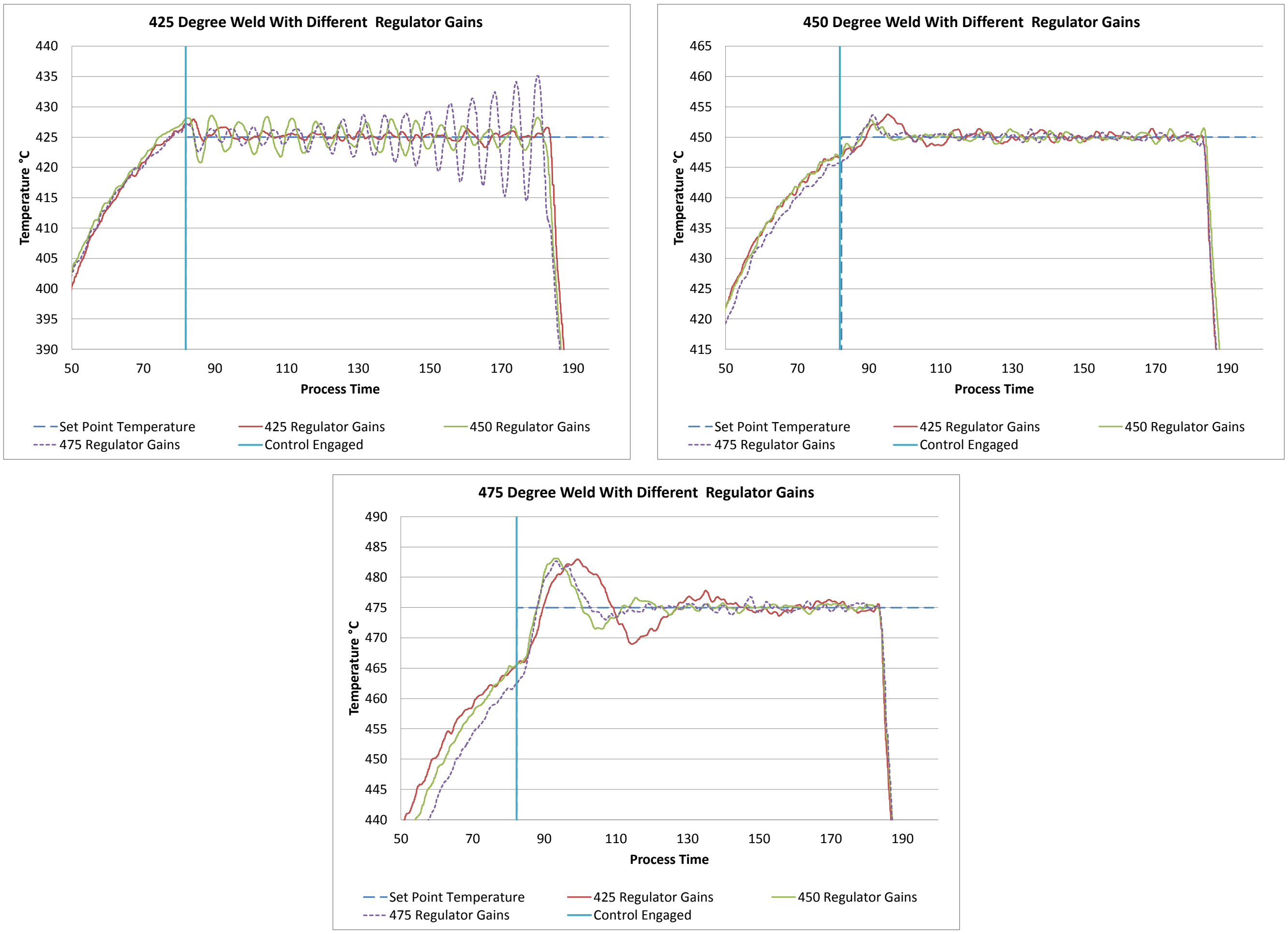

Figure 2.12: The regulator gains determined at 475°C and 450°C were too aggressive to be used for a temperature controlled weld with a set point of 425°C, and caused it to be unstable and marginally stable respectively. The 450°C and 475°C temperature controlled welds exhibited no such effects.

lower temperatures being unstable because the gains push for change in spindle power that is too large for the system to handle. This was seen with the 425°C weld, where the weld went unstable when using the regulator gains determined at 475°C. It was only marginally stable when using the regulator gains determined at 450°C.

2.7 Disturbance Rejection Test Welds

2.7.1 Methods for Aluminum Disturbance Welds

The disturbance rejection welds were run using a set point temperature of 450°C. Three welds were run for each disturbance, one used regulator gains, another used servo gains, and finally one weld was run using constant spindle speed. The 450°C gains from the PID gain temperature sensitivity tests were used for the disturbance rejection testing. A maximum deviation in temperature, and a settling time were calculated for the disturbanced induced temperature error.

Temperature Controlled Weld Over Existing Welds

A weld was run to observe the temperature controllability when running through existing welds and crossing probe extraction holes. The weld was 45 inches in length. The first 4 inches was run with a constant spindle speed before the temperature controller was engaged. The new weld was run over the top of three previously run welds. During the weld, three probe extraction holes were hit. Two were in the middle of the weld, and the third was just prior to weld extraction, and is not readily visible in weld data.

Air Disturbance During a Weld

An air disturbance was used to simulate a fast disturbance. To do this, a compressed air stream was aimed directly at the tool workpiece interface. After the first 4 inches of the weld the temperature controller was engaged. After 7 more inches, the air gun was triggered, and allowed to blow its full capacity for the next 6 inches. The remaining 5 inches were temperature controlled with no disturbances applied.

Feed Ramp During an Existing Weld

Fehrenbacher specifically discussed geometric disturbances related to workpiece geometry. An attempt was made to simulate running a weld with 90° corner. To do this, the feed rate was ramped down from 6 IPM to 2 IPM, and then back up again. This was done to attempt to simulate the build up of heat that would be observed when welding. A 22 inch long weld was run with the

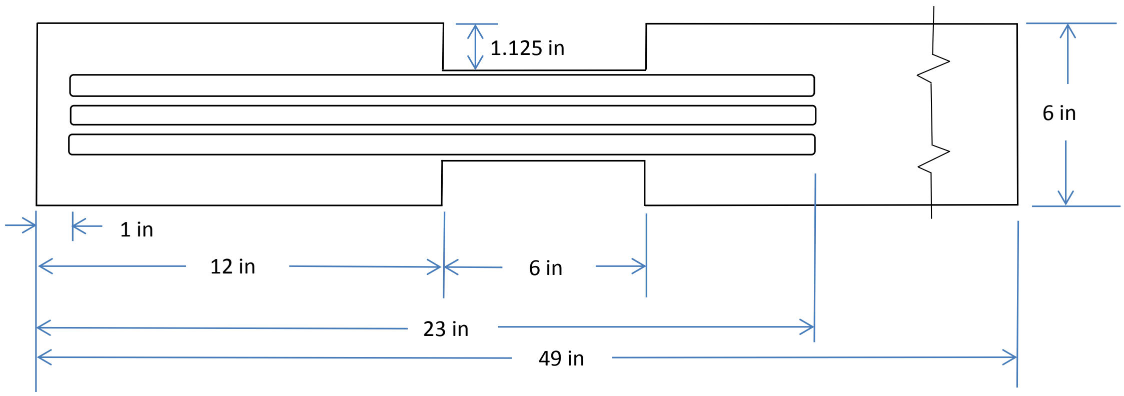

Figure 2.13: Dimensions for a disturbance weld test plate. Side sections of a plate were cut out to do some disturbance testing.

first 4 inches being a constant spindle speed. At 10 inches the feed rate began to ramp down from 6 IPM to 2 IPM. The ramp was 2 inches in length. After ramping down, it immediately ramped back up from 2 IPM to 6 IPM in the same distance. The remainder of the weld was disturbance free.

Plates With A Section Cut Out

Welds were run to determine if geometry has a major influence on the thermal boundary conditions. To test this, a section of a plate was removed on either side of the three welds, and welds were run. Figure 2.13 depicts the dimensions of the plate and the sections which were removed. The weld was started with a 4 inch section to reach temperature, and then the rest of the was either temperature controlled, or run at a constant spindle speed.

Oil On A Plate

A layer of oil was applied to a section of the plate to determine if an oily plate surface versus a non-oily plate surface had an effect on temperature. The weld was started as normal with the first 4 inches in spindle speed control to get the temperature up. The remaining 18 inches were either temperature controlled or had a constant spindle speed. Oil was spread across the surface of the plate from 11 inch to 17 inch portion of the weld.

2.7.2 Disturbance Weld Results Aluminum

Five different types of disturbance welds were run in aluminum as described previously. The controllers performed as expected, with the regulator gains maintaining temperature the best, and with the constant spindle speed being least capable to maintain a steady temperature.

The most dramatic disturbance tested was running over a set of existing welds, and hitting two extraction holes in the process. The temperature controllers were able to control weld temperature with no difficulty in previously welded material, but the pin holes were a problem. The controllers were not able to control temperature while crossing the pin holes. Similarly, a constant spindle speed dropped temperature significantly when crossing the pin holes. It can be seen in Figure 2.14 that the servo control responded best to this disturbance because it was still a form of active control, but it wasn't pushing so hard as to introduce the major overshoot produced by the regulator control. After hitting the probe extraction holes it took 35-40 seconds for all three control methods to return back to a steady state condition, though it can be seen that the spindle speed is still somewhat transient afterwards. The results for all the disturbance welds are summarized in Table 2.7.

Table 2.7: A summary of the results from the aluminum disturbance rejection welds. The settling time is the time to be within 2°C of the pre-disturbance temperature, or return to steady state conditions.

	Error (°C)	Settling Time (s)	Oscillations
Run Over Existing Welds Regulator	36	35-40	3
Run Over Existing Welds Servo	20	35-40	2
Run Over Existing Welds Spindle Speed	38	35-40	1
Air Blast Regulator	4.0	11.7	0
Air Blast Servo	6.5	Steady State Error	0
Air Blast Spindle Speed	28	130	0
Feed Ramp Regulator	0	0	0
Feed Ramp Servo	3.5	5.4	0
Feed Ramp Spindle Speed	6.0	83	0
Oil on Plate Regulator	0	0	0
Oil on Plate Servo	0	0	0
Oil on Plate Spindle Speed	3.0	0	0
Plate Cut Out Regulator	0	0	0
Plate Cut Out Servo	1.5	0	0
Plate Cut Out Spindle Speed	7.0	89	0

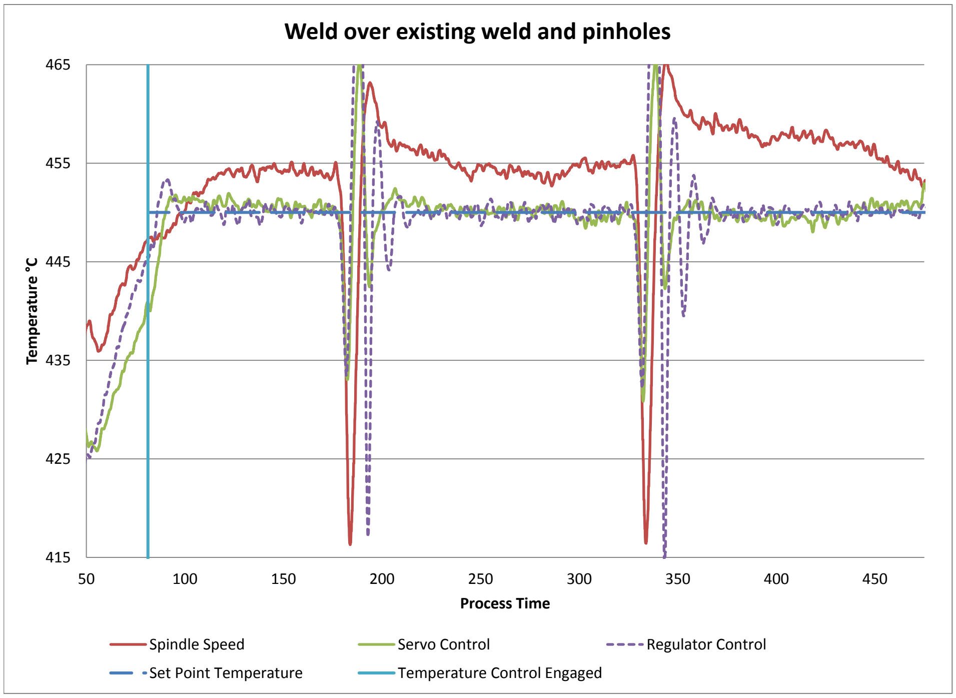

Figure 2.14: Welds were run to test the temperature controllability across existing welds and probe extraction holes. This test was run to observe what may happen when reaching an existing weld.

The air blast directed towards the tool-workpiece interface was the next most difficult disturbance to handle. It can be seen in Figure 2.15 that the regulator controller maintained temperature well, with only a brief error of 4°C at the start and end of the air blast. The servo controller kept the temperature close to the 450°C error with a maximum error of about 6.5°C at both the start and end of the air blast. It did however have steady state error throughout the disturbance, and also after it. There was a 28°C temperature drop in the tool temperature of the constant spindle speed weld. The regulator gains had a settling time of about 12 seconds. The servo gains had no true settling time because of the amount of steady state error. Similarly, the constant spindle speed welds had no true settling time, but became steady state again at about 130 seconds.

The other three disturbances only had minor effects on temperature. The feed rate was ramped down and up to simulate approaching a corner. This only had a minor effect on temperature, and minimal error was observed in the servo weld, and no noticeable error was observed on the regulator weld. The spindle speed weld experienced about a 6°C rise in temperature during the ramping down and up of the feedrate. After the ramp was finished, the temperature decreased again.

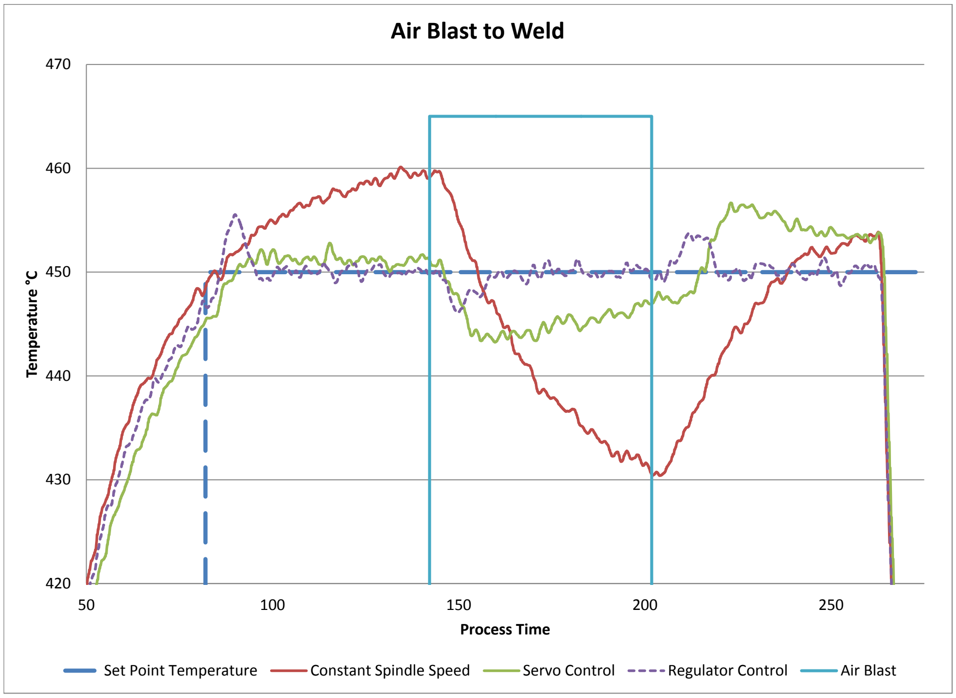

Figure 2.15: During a temperature controlled weld, an air blast was applied to the tool workpiece interface to simulate a fast acting disturbance to the process.

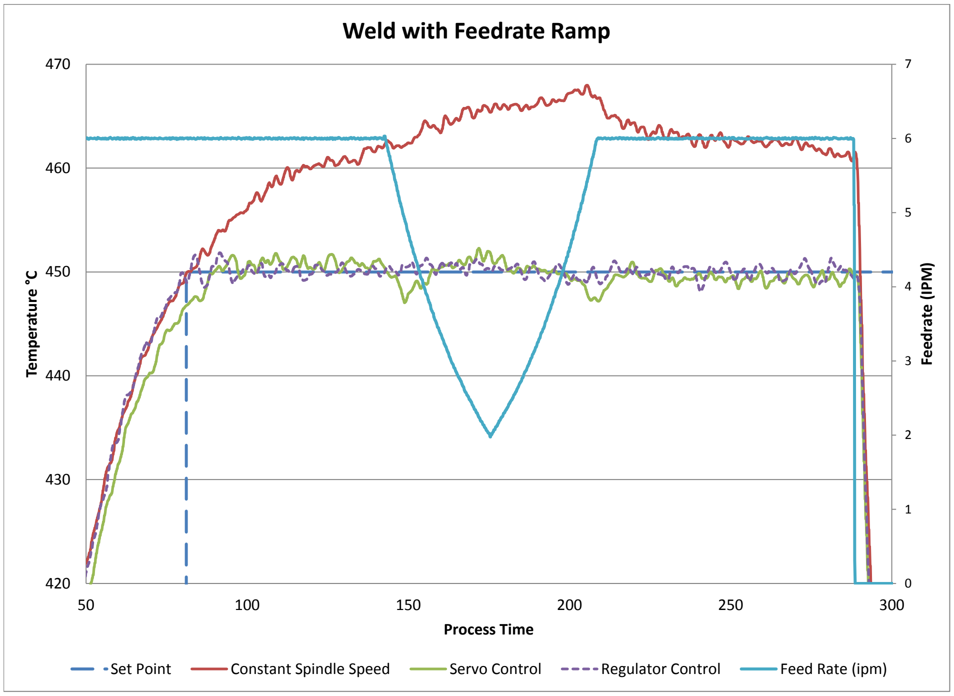

Figure 2.16: The feedrate was ramped down and back up again during the midsection of a weld to simulate approaching a sharp corner during a weld.

Figure 2.17: Side sections of a plate were removed to simulate a geometric disturbance.

A section of the plate being welded was cut out. The effect of this was to simulate a geometric change. It can be seen that both servo and regulator control worked well at controlling the temperature. The servo controller had about 1.5°C of steady state error that remained steady though out the cut out. The constant spindle speed section dropped temperature about 7°C during the cut out, and had a long settling time of about 90 seconds. The temperature controller had a settling time of 0 seconds for both the regulator and servo gains.

Covering a section of the plate with oil seemed to have no significant effect on temperature. While the weld was being run, the oil was chased away by the heat before the tool reached it. It can be seen that both servo and regulator gains controlled the temperature at 450°C with no significant error. The constant spindle speed weld dropped temperature about 3°C during the weld, but it is unclear if it is related to the oil being on the plate. For these welds, all three welds essentially had a settling time of 0 seconds, since the constant spindle speed section experienced a large disturbance in temperature, and the cause of the minor deviation is unclear.

Overall it can be seen that temperature control is able to reject disturbances, and maintain temperature with minimal error. The exception to this is traversing the existing pin holes, where the

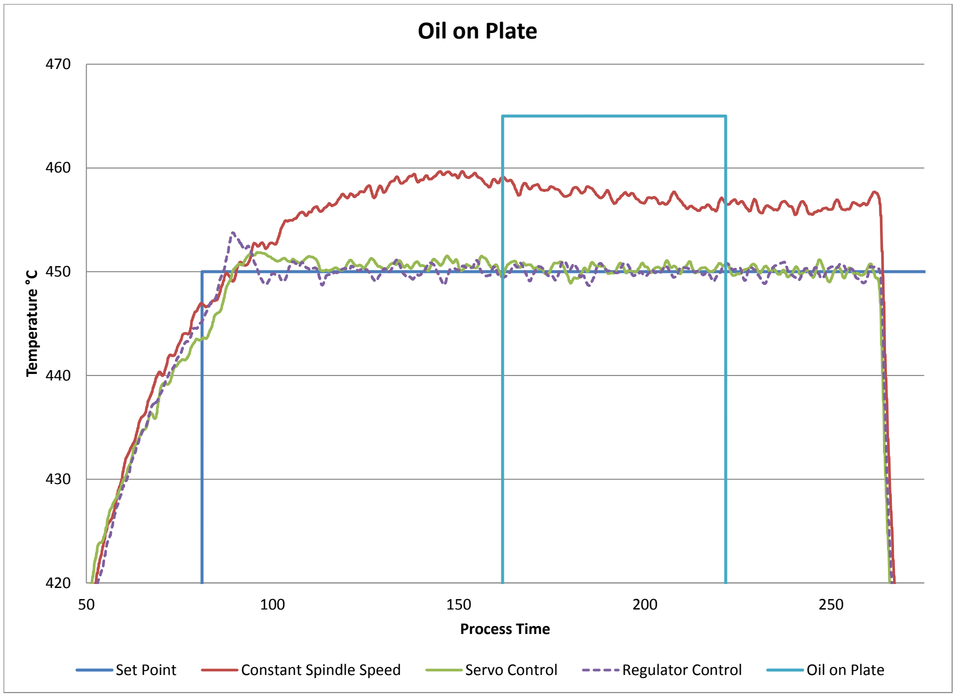

Figure 2.18: Oil was spread across a section of a plate to determine if oil on a plate affected the temperature controllability.

controller attempted to maintain temperature, but was unable. As expected regulator control does best at rejecting the disturbances. With the exception of the air blast and pin hole disturbances, the servo gains were able to handle and reject the disturbances with no significant error to the tool temperature. Additionally, because of the aggressive nature of the regulator gains, a larger error in temperature was observed while traversing the pin hole, than what is observed with the servo controlled and constant spindle speed welds.

2.7.3 Discussion Aluminum Disturbance Welds

It was seen that the temperature controller was unable to maintain temperature when welding over the existing extraction holes. Upon a review of the force pressing the tool against the plate, it was seen that the force dropped from approximately 6,000 lbs to only 2,000 lbs when crossing the extraction holes. It is believed that this resulted in the extraction holes being uncontrollable. With such low forces, not enough heat was being generated to maintain or adjust temperature.

2.7.4 Methods for Steel Disturbance Welds

In addition to the temperature welds, two disturbance welds were run in steel. These welds used the PID gains from the third relay weld. The disturbances were run with regulator gains at 800°C. The welds included an air blast and a change in feed rate as disturbances.

Air Disturbance During a Weld

An air disturbance was applied during the steel weld. The first 6 inches were allowed for the tool to reach temperature. The controller was then activated. The air blast was applied near the tool workpiece interface from 12-17 inches. After the 17 inches, the weld was run in temperature control mode until the tool extraction.

Feed Ramp During an Existing Weld

A weld was run with a change in feedrate mid-weld. The weld had 6 inches to allow the weld and tool to come up to temperature. At 6 inches the controller was engaged using servo gains. At 12 inches, the controller switched to regulator gains, and the feed rate began to ramp down from 6 IPM to 2 IPM. It did this over 5 inches. At 17 inches, feed rate was ramped back up from 2 IPM to 6 IPM. At 22 inches the tool was extracted.

2.7.5 Disturbance Weld Results Steel

Two disturbance welds were run using the system parameters from the third relay that was run. One disturbance weld was subjected to an air blast, and the other had the feed rate ramped down and back up again. The controller was unable to maintain the tool temperature on either of these welds. During the air blast weld, the thermocouple measured a 175°C decrease in temperature as seen in Figure 2.19. The controller attempted to compensate by increasing power. The spindle speed climbed dramatically. This resulted in a visible weld defect.

The feedrate was ramped down, and then back up again on the second disturbance weld. During the initial phase of the ramp, an oscillation in temperature began. The controller was unable to maintain temperature. This weld also developed a visible weld defect. The reason for

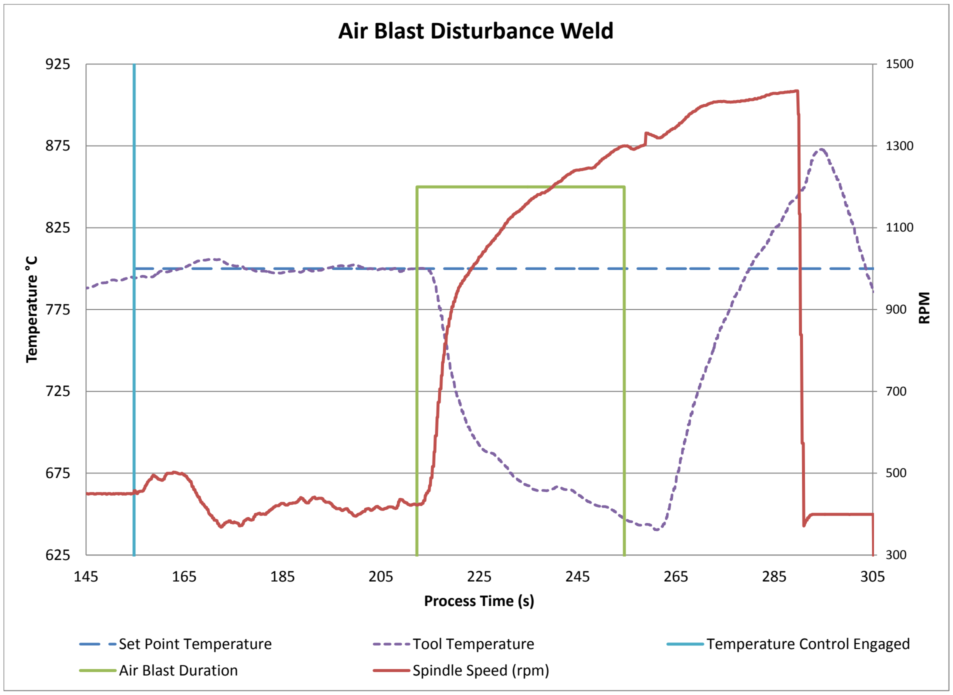

Figure 2.19: An air blast disturbance during a steel weld

the oscillation in this weld is unknown. It appears however to have become unstable during the change in feed rate as seen in Figure 2.20.

2.7.6 Discussion Steel Disturbance Welds

The temperature controller was unable to control the temperature during the air blast on the steel weld. During this weld, the tool workpiece interface was still red hot. From what was observed, it is believed, that the heat was being carried away primarily from the thermocouple and not the weld, resulting in a seemingly low weld temperature that did not exist. The controller responded accordingly, by providing more power. Additionally, the argon shielding was lost by using an air blast. An incorrect temperature measurement could more easily occur in a tool with the thermocouple located above the shoulder, near the outside of the tool. The aluminum tools had thermocouples located below the shoulder in the center of the pin, protecting it from heat loss to the tool surface. Between the increase in power, which resulted in high spindle speeds, and the lack of argon shielding, the weld failed to consolidate.

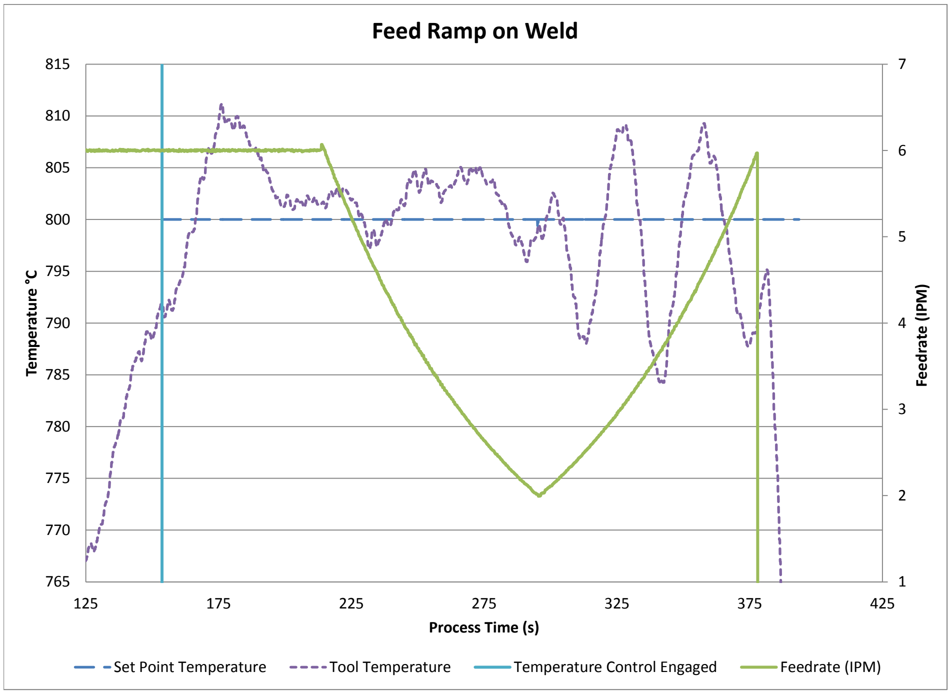

Figure 2.20: The feedrate was ramped down and back up again during the midsection of a weld to simulate approaching a sharp corner during a weld.

The steel weld with the changing feedrate similarly failed to consolidate. The reason for the lack of weld consolidation is unknown, however, it can be seen that there is large oscillation in temperature. This oscillation was led by an oscillation in spindle power and in turn spindle speed as seen in Figure 2.21. It is believed that this large dramatic change in spindle speed may have caused the formation of the weld defect. The reason for the oscillation in spindle power is unknown. It is possible that the system model changed enough with feedrate to introduce a large oscillation into the system.

2.8 Conclusion

The relay feedback test has been used to determine FOPDT system parameters for friction stir processing in 7075-T6 aluminum, and cold rolled steel. These FOPDT system parameters were used to calculate PID gains, that were used with a PID controller, to control the tool temperature. Both servo and regulator gains demonstrated good temperature control in both aluminum and steel. The servo gains would bring the temperature close to the set point, but tended to experience 1-2°C

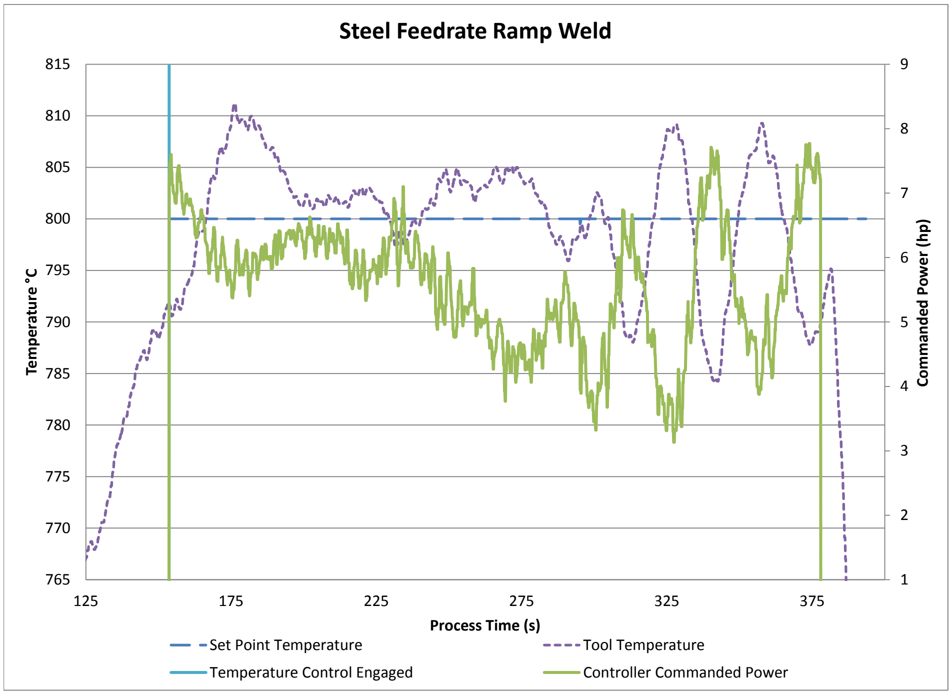

Figure 2.21: The feedrate was ramped down and back up again during the midsection of a weld to simulate approaching a sharp corner during a weld. This weld shows the commanded power throughout the weld cycle.

of steady state error in aluminum, and about 3°C of error in steel. The regulator gains eliminated steady state error in both aluminum, and steel.

The relay feedback test can be run in a short length. In aluminum, it was observed that the relay feedback test can be run in 6 inches of length while using a feedrate of 6 IPM. At 425 and 450°C, this allowed the system to fully cycle 5 times. At 475°C, it fully cycled 4 times. In steel, the relay feedback test fully cycled 4 times in 12 inches. The relay feedback test is able to determine system parameters in this time and has demonstrated the ability to control temperature.

The system parameters change with temperature. The process gain (K_m) decreases with increasing temperature, the time constant (τ) increases with increasing temperature, and the time delay (θ) is not significantly affected by temperature.

In aluminum, all of the servo gains were capable of controlling temperature at 425-475°C, but the regulator gains were less capable of controlling temperature with stability when the set point temperature was lower than the temperature the relay welds were run at. It can be concluded that when using servo gains, the relay should be run close to the desired set point temperature, but that some degree of variation is allowable both above and below the set point with no notable change in controllability. When using regulator gains, the relay weld should be run at or below the desired set point temperature to prevent instabilities from occuring.

In aluminum, the disturbance rejection gains handled most disturbances with less than a 5°C change in temperature. The exception to this was welding over the existing weld retract pin holes, which caused a variation of 36°C. The servo gains did well, but in addition to struggling with running over existing probe extraction holes, the servo gains experienced a 6°C error in the temperature on the air blast disturbance. With all the other disturbances, the servo gains displayed less than a 5°C error in reaction to the disturbances.

When compared with the spindle speed control, the regulator gains offers much better control. It can be seen in the disturbance welds, that a constant spindle speed allows the temperature to move around significantly. On the air blast disturbance welds, the constant spindle speed weld lost approximately 30°C and requires about 130 seconds to return to a steady state condition, where the regulator controller kept the temperature within about 4°C, and quickly returns to the set point in 12 seconds. When disturbances are present, the temperature controller minimizes the error, where a constant spindle speed controller has no effect and will only return to a quasi steady state condition after any major disturbance is removed.

When using the relay feedback test in friction stir processing, it is recommended that the test is run long enough to allow the temperature to cycle at least 4 times. When determining servo type gains from the system parameters, it is recommended that the relay feedback test be run at a temperature either at or below the desired set point temperature. When determining servo type gains, the relay feedback test can be run at a temperature either above or below the desired set point, but it should be somewhere close to the desired set point temperature. When this is done, the relay feedback test should provide system parameters which are capable of providing controller gains that will control temperature with stability and minimal error.

CHAPTER 3. FUTURE WORK

The relay feedback test is often implemented in industrial controllers such as PLCs. When this is done, the process is often automated to allow online tuning. One area of research that would be beneficial would be having online tuning so that no additional post processing would be required. This would allow a temperature controlled weld to be run directly following a relay test.

System identification and temperature control work should be done in the plunge and initial traverse sections of a weld, to improve the process control. It is possible to use temperature control at the beginning of the weld, but the initial error may be unpredictable and quite large.

Work has been done to study the effect backing plates have on weld properties, but no work has been done comparing the effect that different backing plates have on system parameters and the temperature controllability.

It can be seen in the relay welds for steel and aluminum, that there is a notable difference between the temperature signals from the tool. Work should be done to determine why or how the PCBN tools for welding steel are different than those used for welding aluminum.

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APPENDIX A.

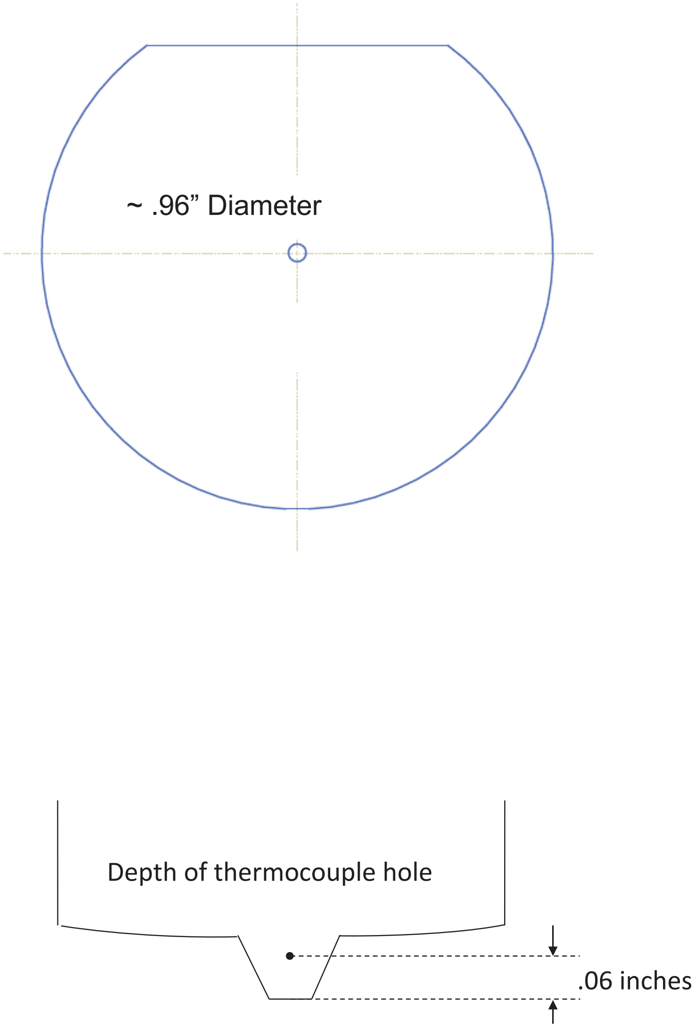

Figure A.1: This Figure shows the depth of the thermocouple hole in the CS4 tool used for the aluminum relay and temperature welds.

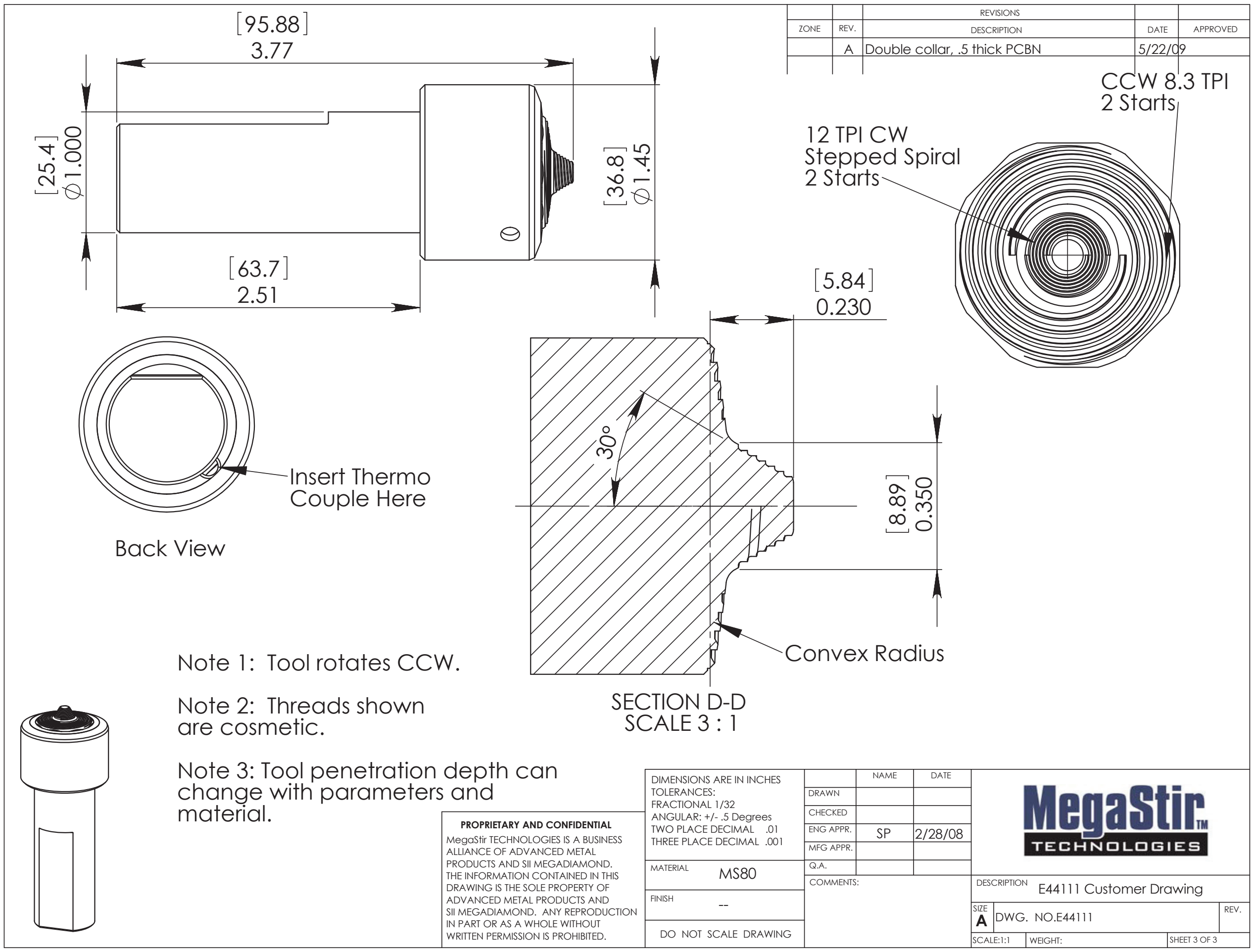

Figure A.2: Dimensions And Details for Tool E44111

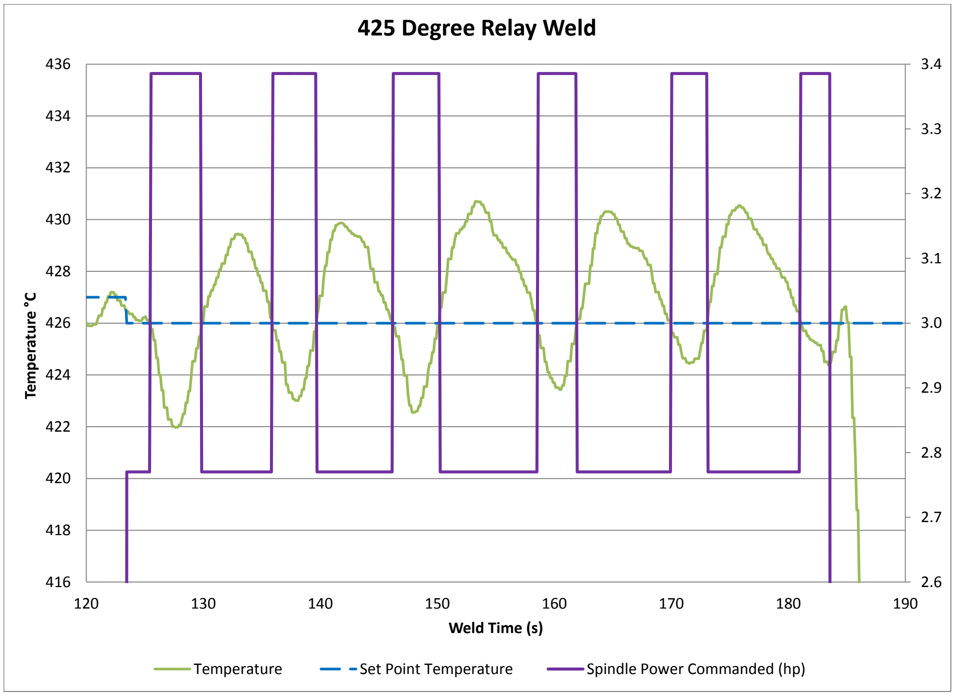

Figure A.3: 425°C Relay Weld 1

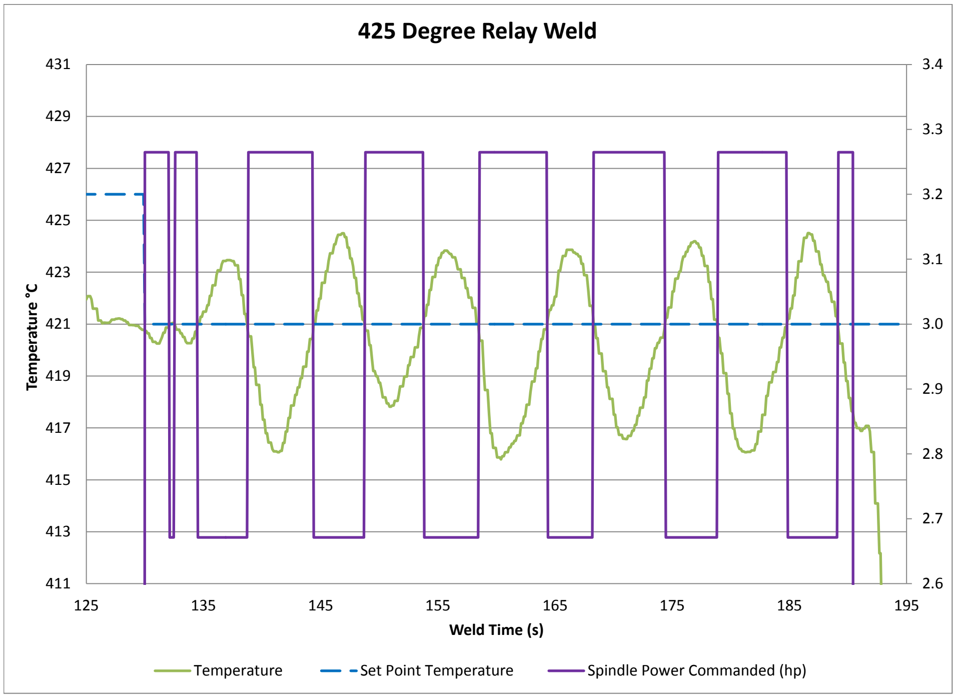

Figure A.4: 425°C Relay Weld 2

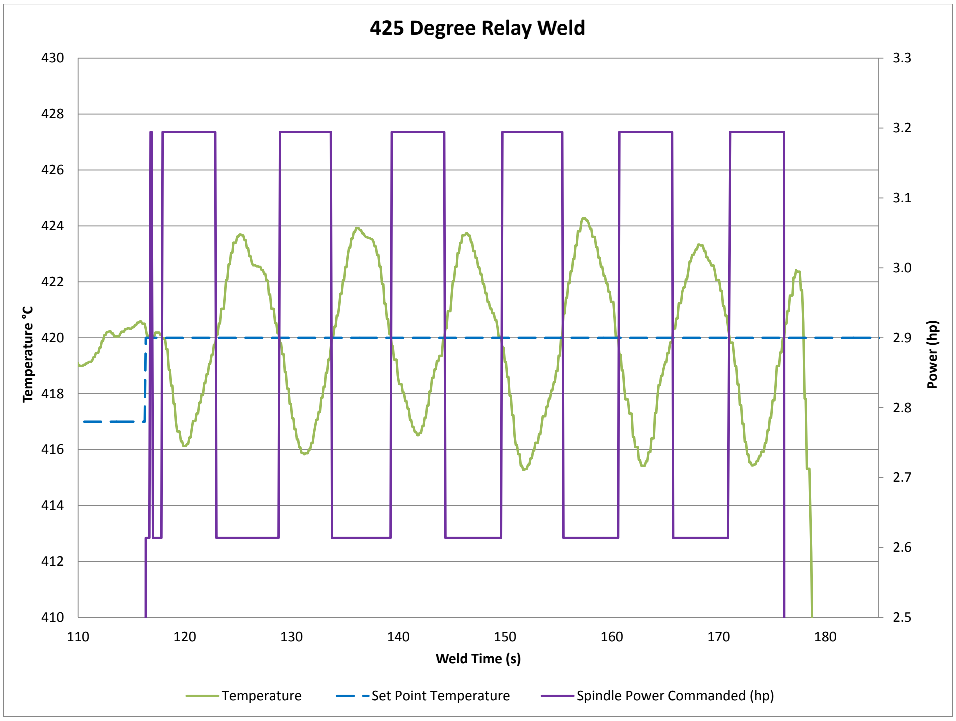

Figure A.5: 425°C Relay Weld 3

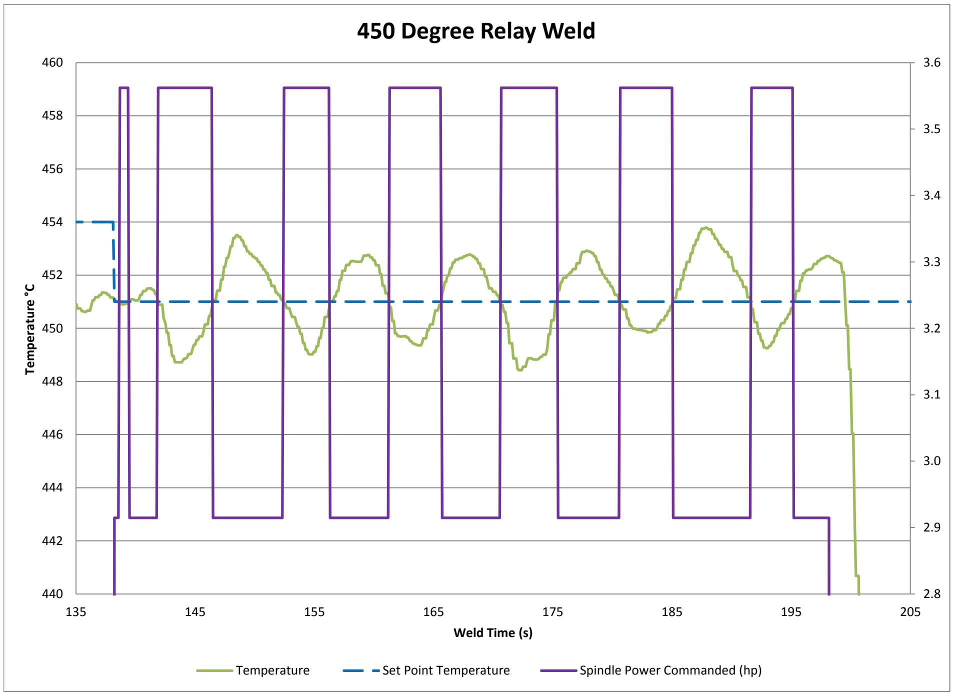

Figure A.6: 450°C Relay Weld 1

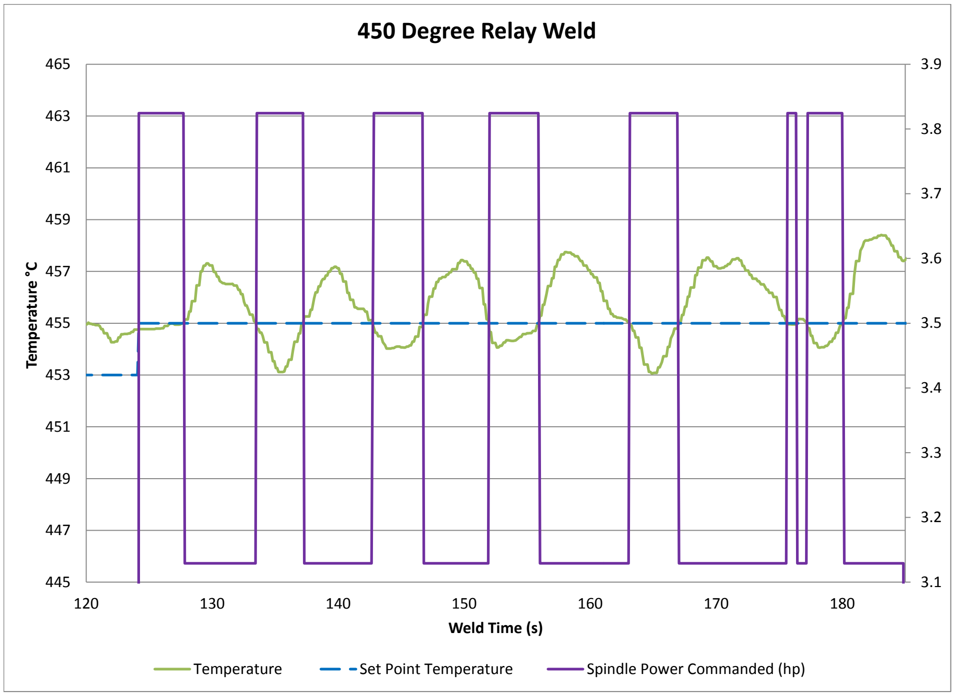

Figure A.7: 450°C Relay Weld 2

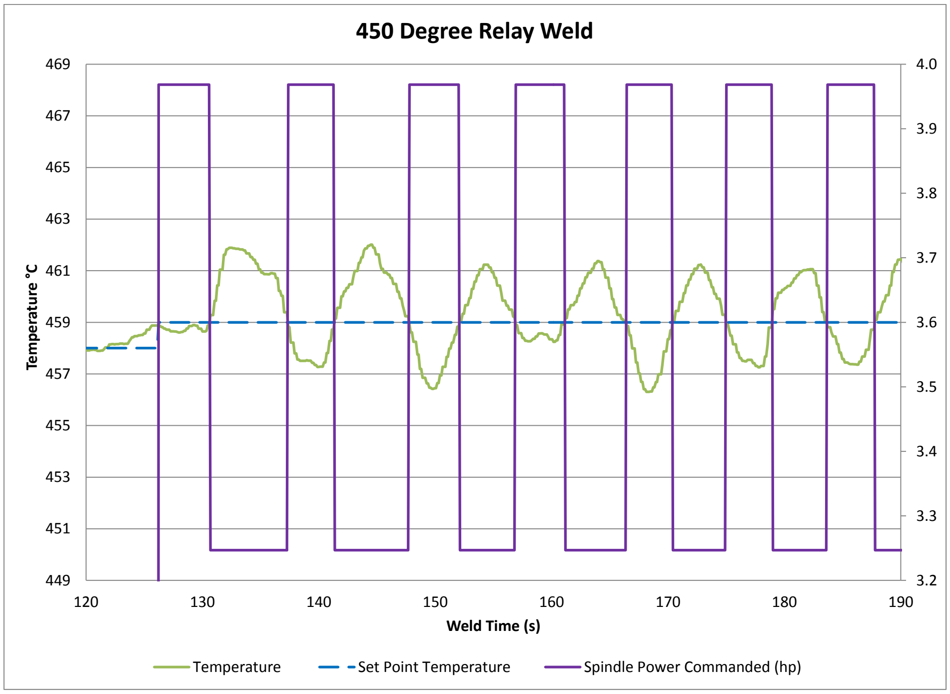

Figure A.8: 450°C Relay Weld 3

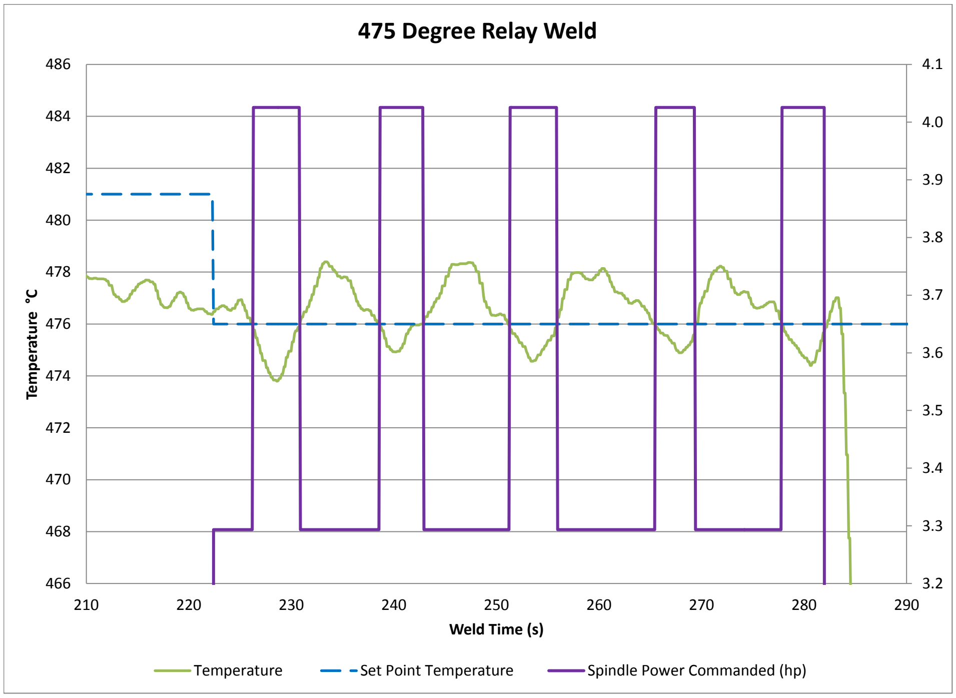

Figure A.9: 475°C Relay Weld 1

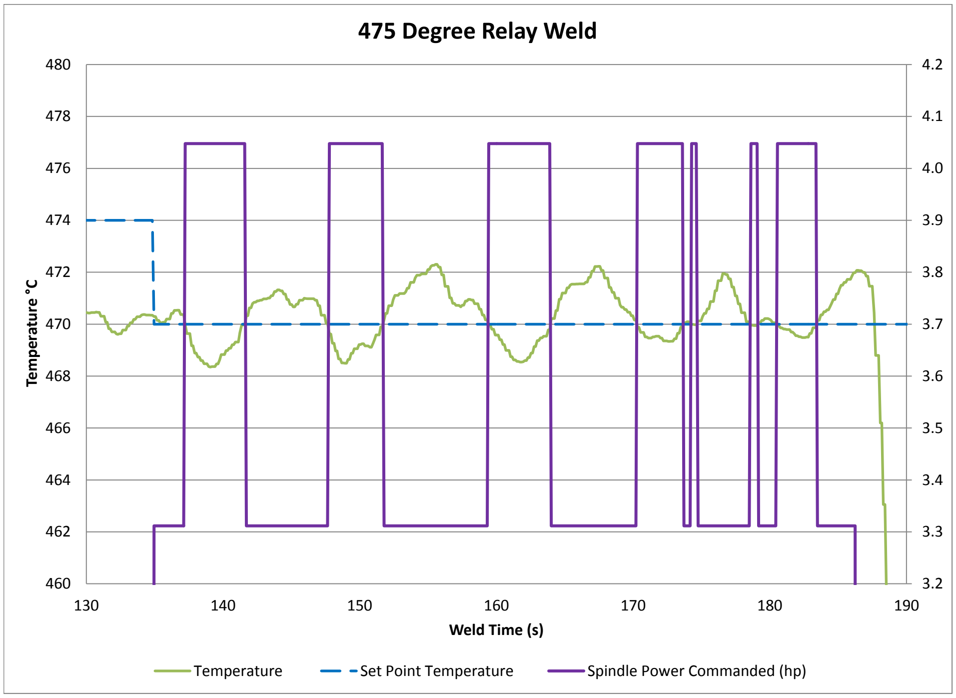

Figure A.10: 475°C Relay Weld 2

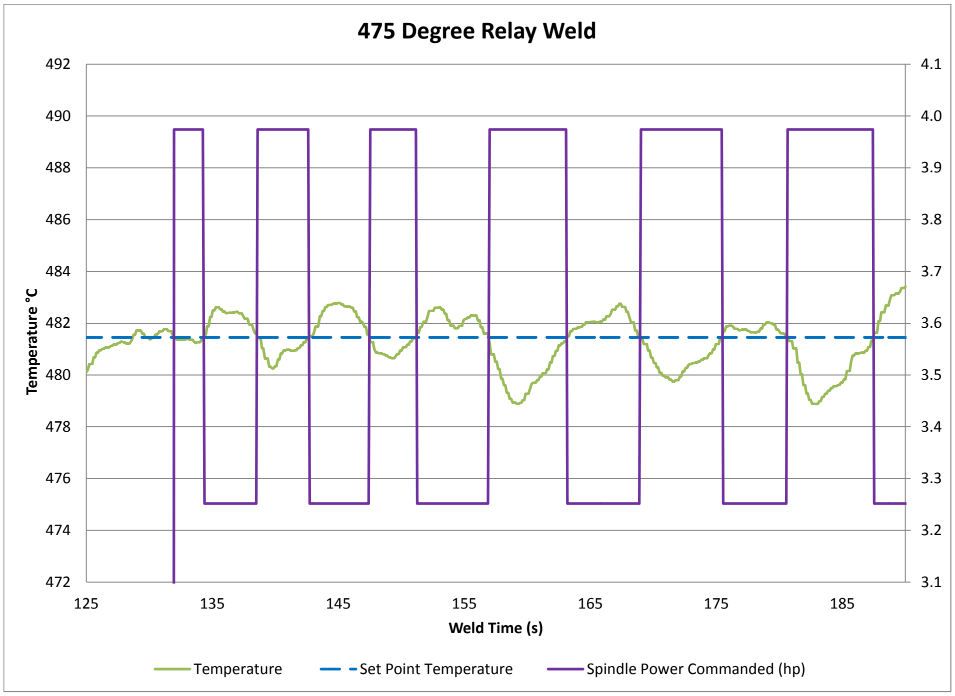

Figure A.11: 475°C Relay Weld 3

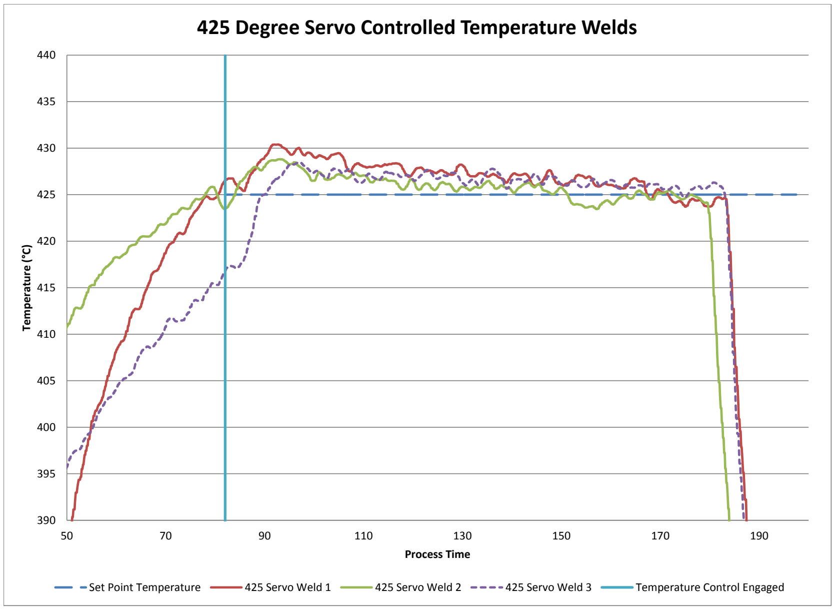

Figure A.12: 425°C Temperature Controlled Weld Using Servo Gains

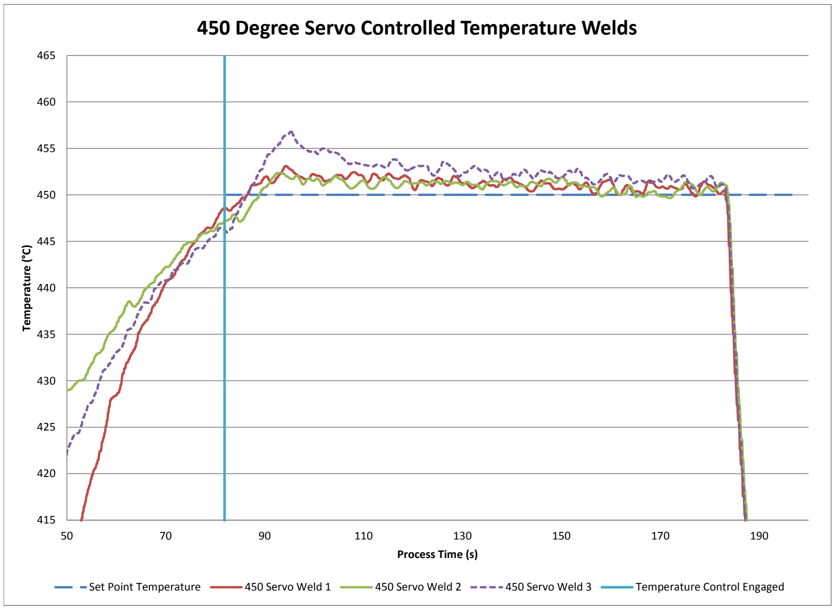

Figure A.13: 450°C Temperature Controlled Weld Using Servo Gains

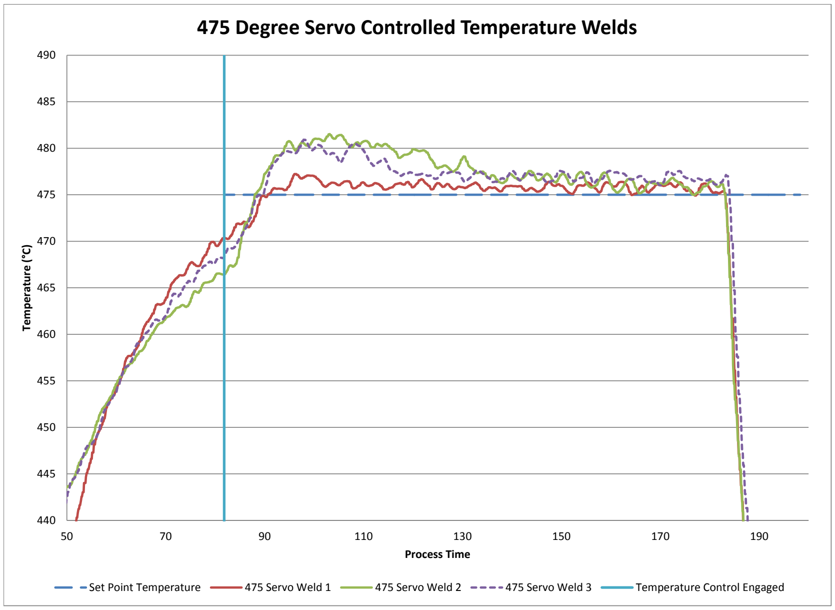

Figure A.14: 475°C Temperature Controlled Weld Using Servo Gains

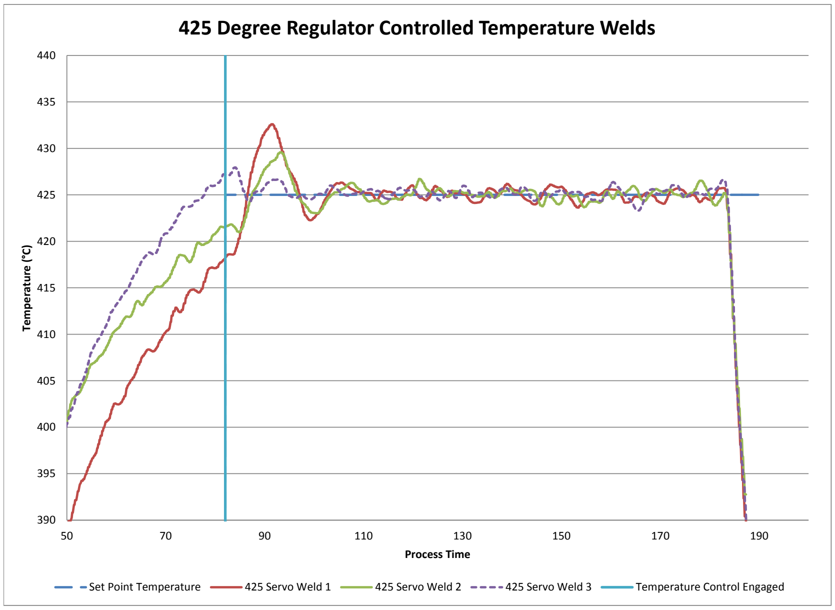

Figure A.15: 425°C Temperature Controlled Weld Using Regulator Gains

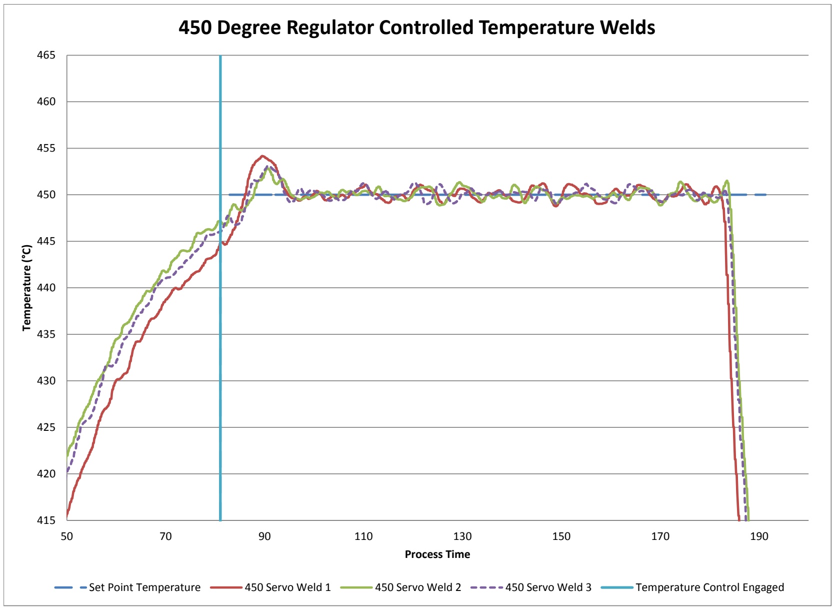

Figure A.16: 450°C Temperature Controlled Weld Using Regulator Gains

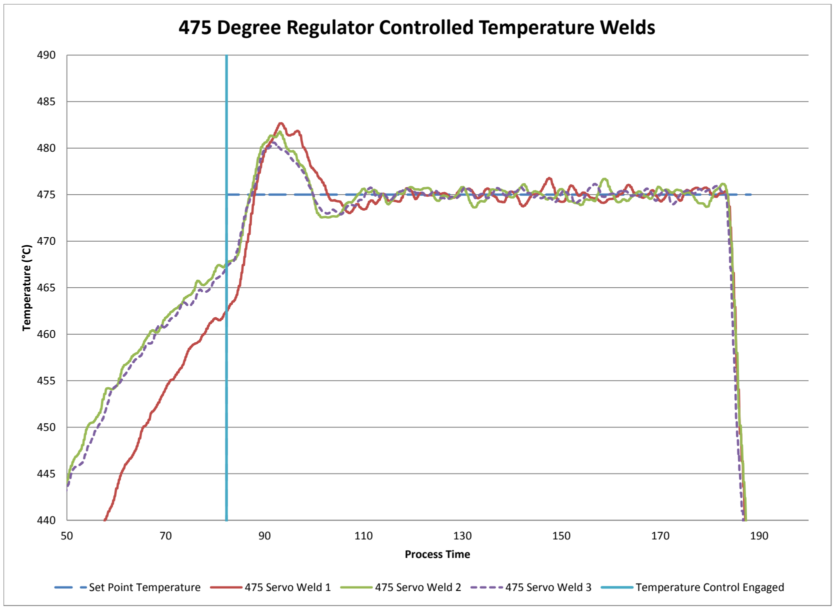

Figure A.17: 475°C Temperature Controlled Weld Using Regulator Gains

APPENDIX B.

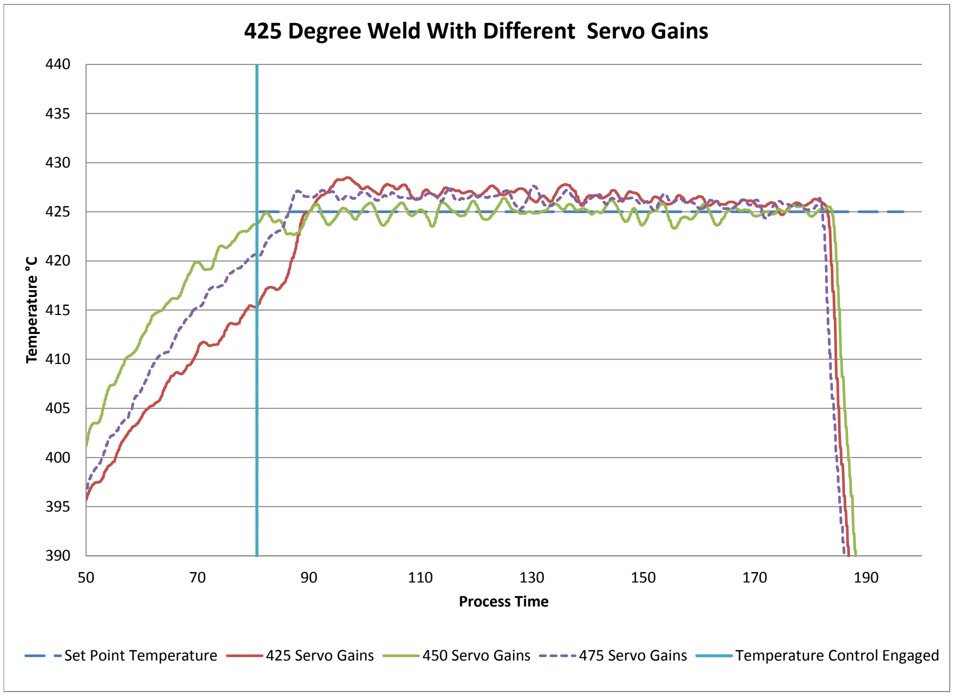

Figure B.1: 425°C temperature controlled welds comparing servo gains from different temperatures.

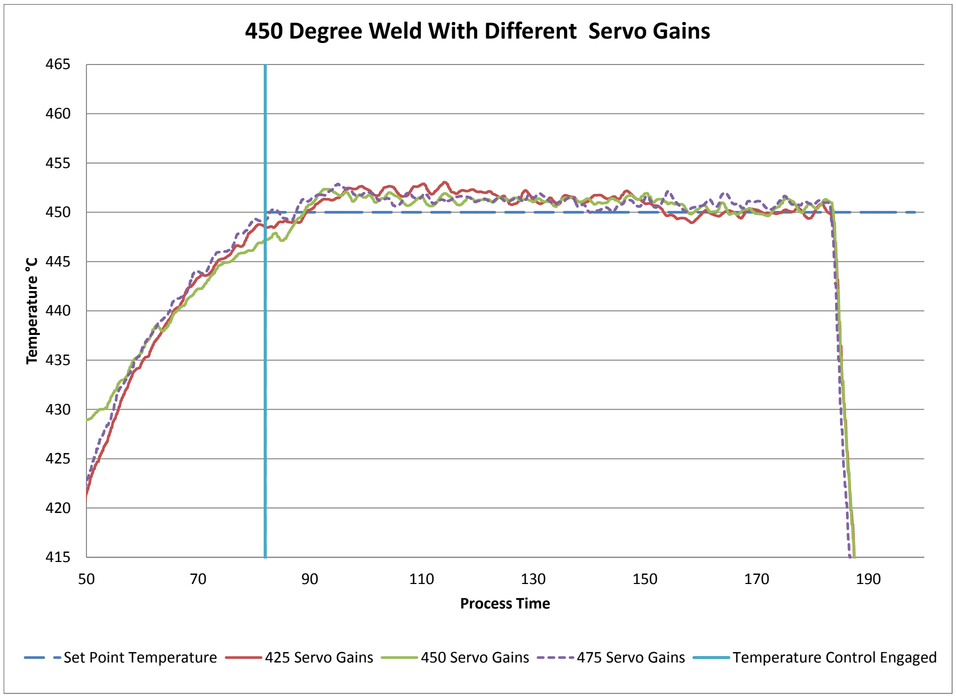

Figure B.2: 450°C temperature controlled welds comparing servo gains from different temperatures.

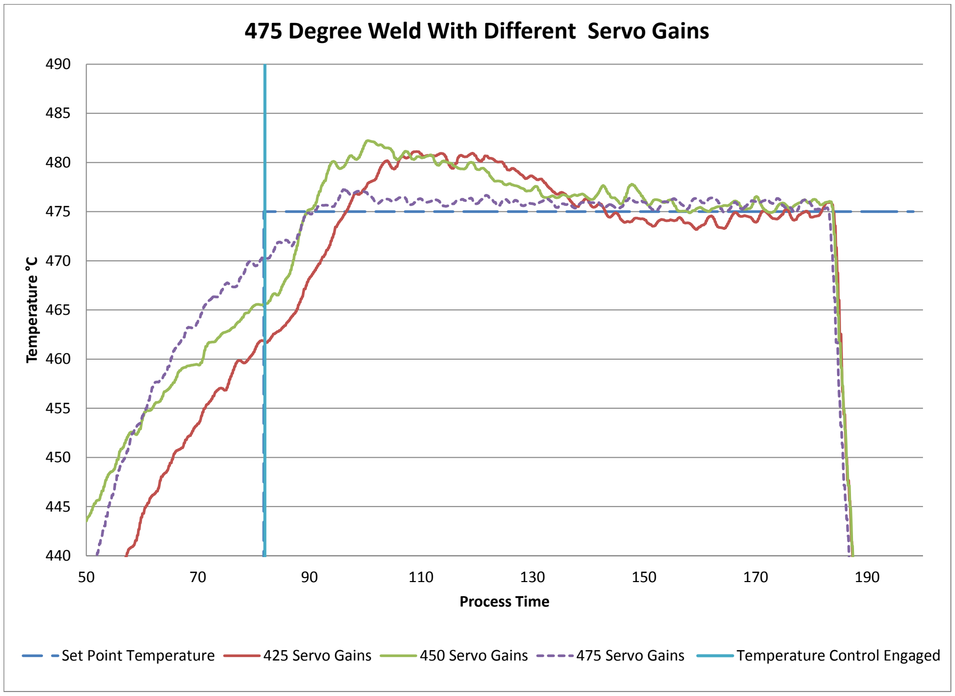

Figure B.3: 475°C temperature controlled welds comparing servo gains from different temperatures.

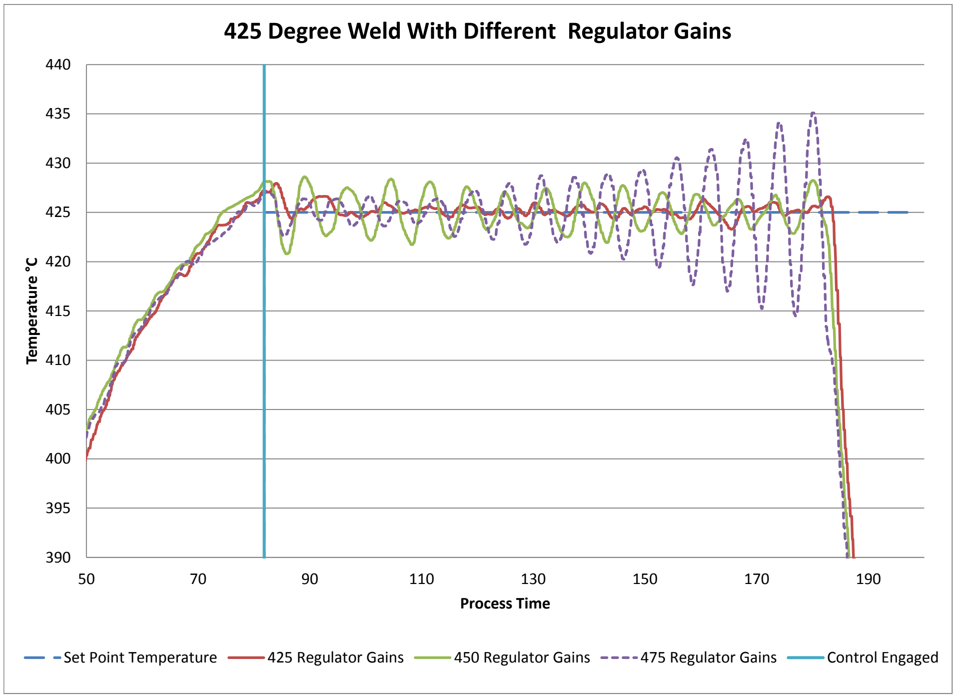

Figure B.4: 425°C temperature controlled welds comparing regulator gains from different temperatures.

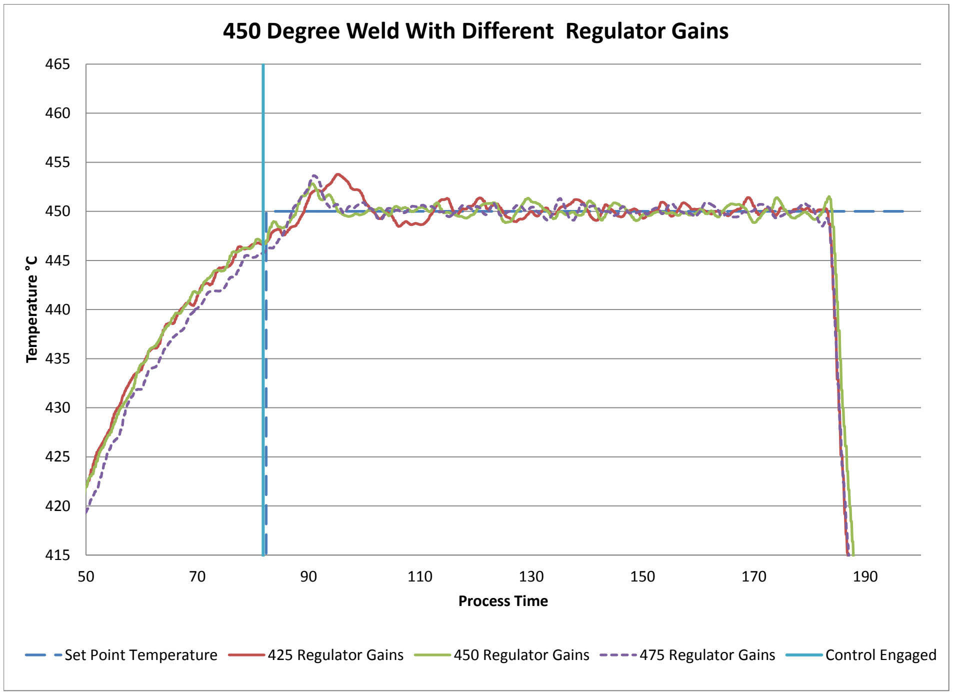

Figure B.5: 450°C temperature controlled welds comparing regulator gains from different temperatures.

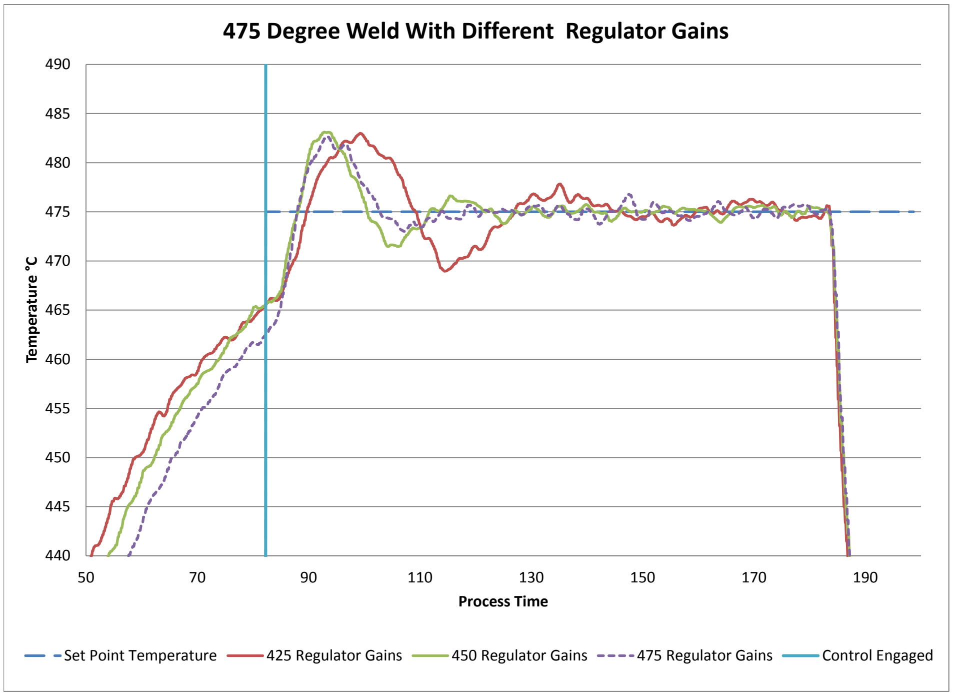

Figure B.6: 475°C temperature controlled welds comparing regulator gains from different temperatures.

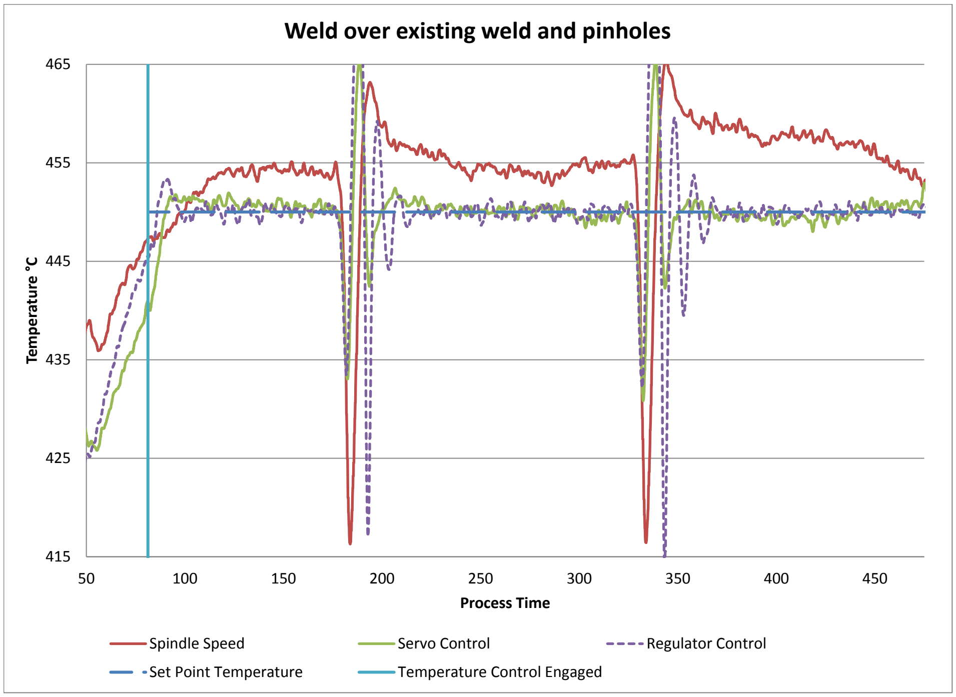

Figure B.7: Temperature controlled welds were run over three existing aluminum welds. During the weld, two pinholes were traversed which acted as large disturbances.

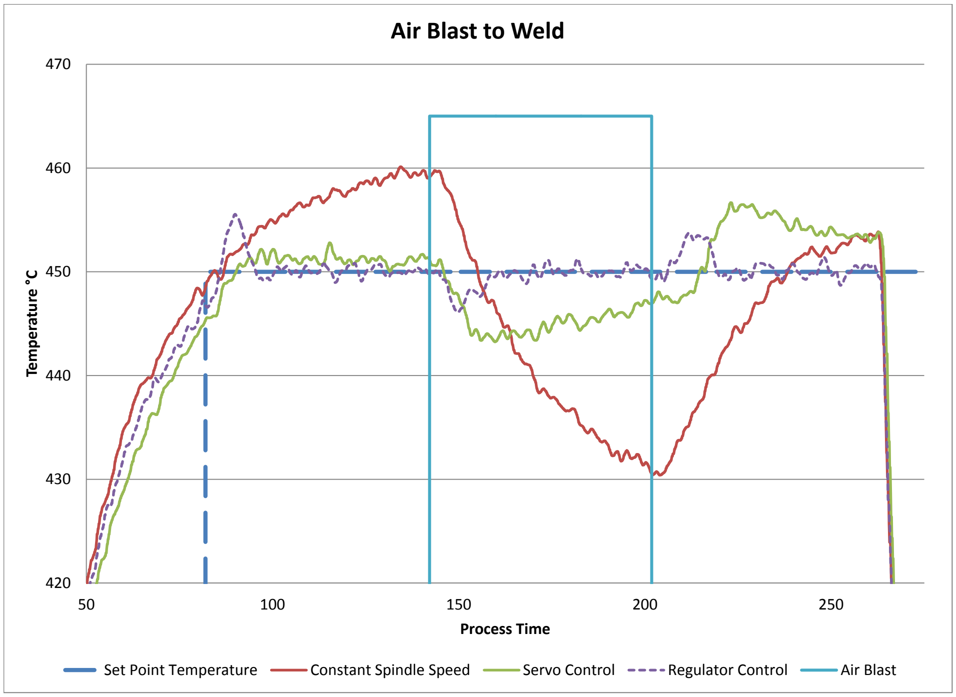

Figure B.8: Temperature controlled welds were run in aluminum; part way through the weld, an air blast was directed at the tool workpiece interface to act as a fast acting disturbance to the weld temperature.

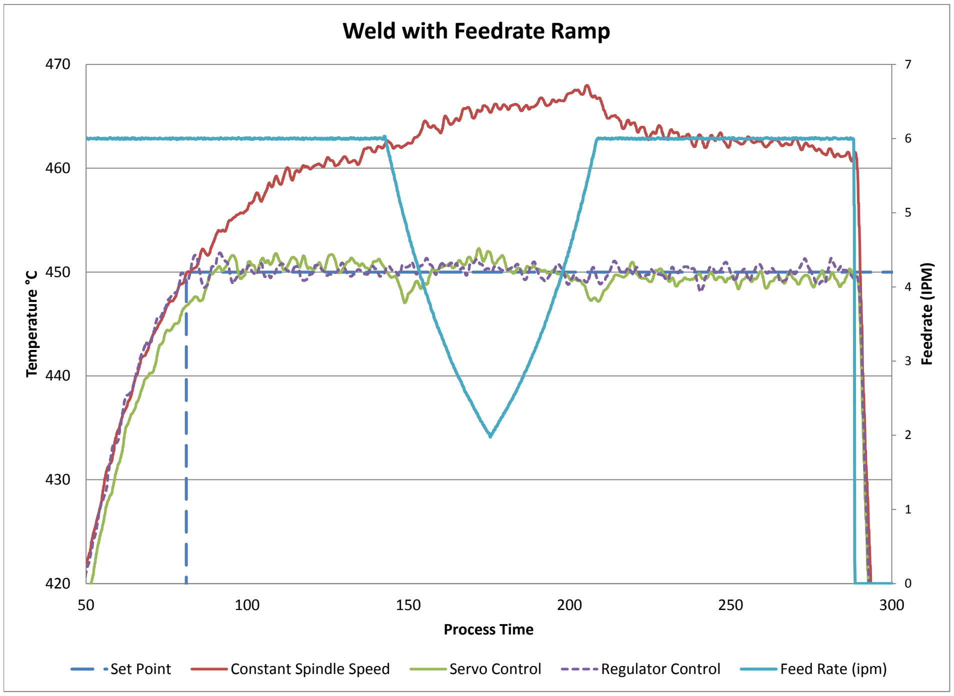

Figure B.9: Temperature controlled welds were run in aluminum; during the weld, the feed rate was adjusted to try and replicate a geometric disturbance.

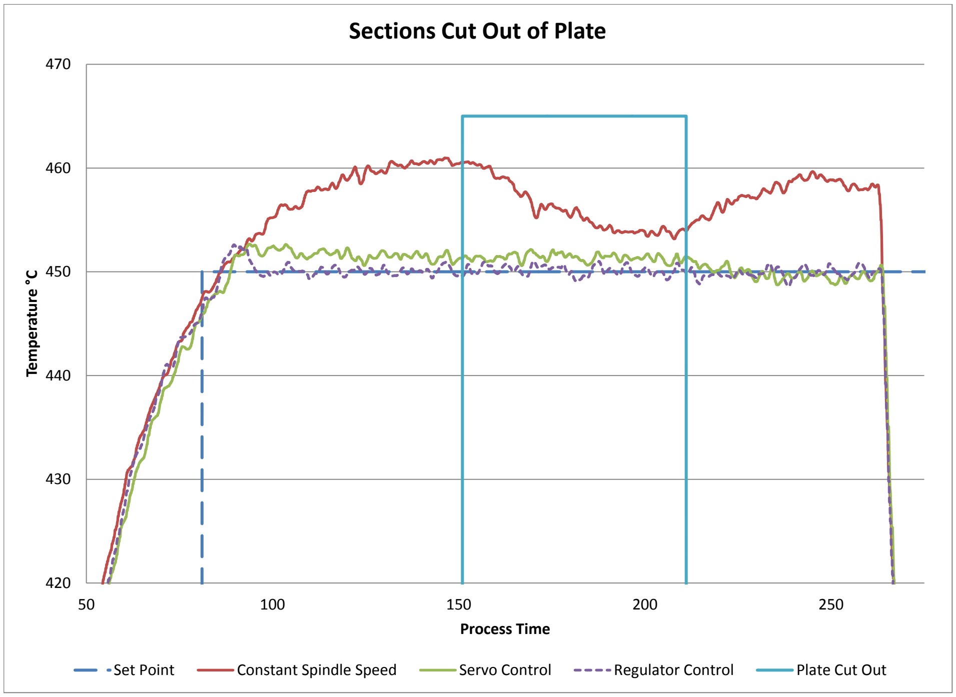

Figure B.10: Temperature controlled welds were run in an aluminum plate with sections cut out.

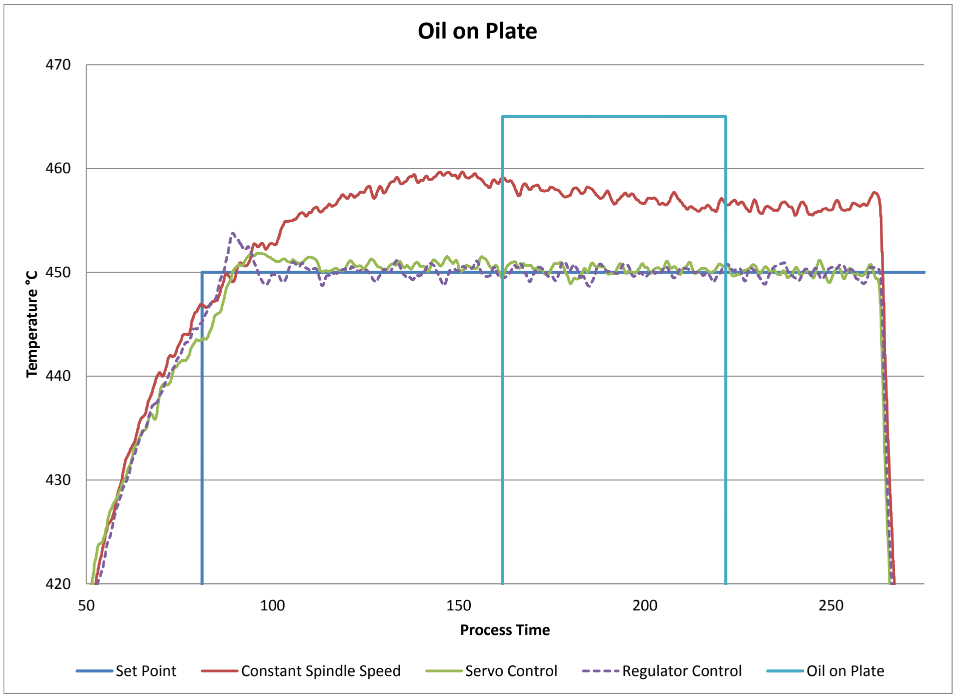

Figure B.11: A temperature controlled disturbance weld run with a section of oil covering the plate surface.

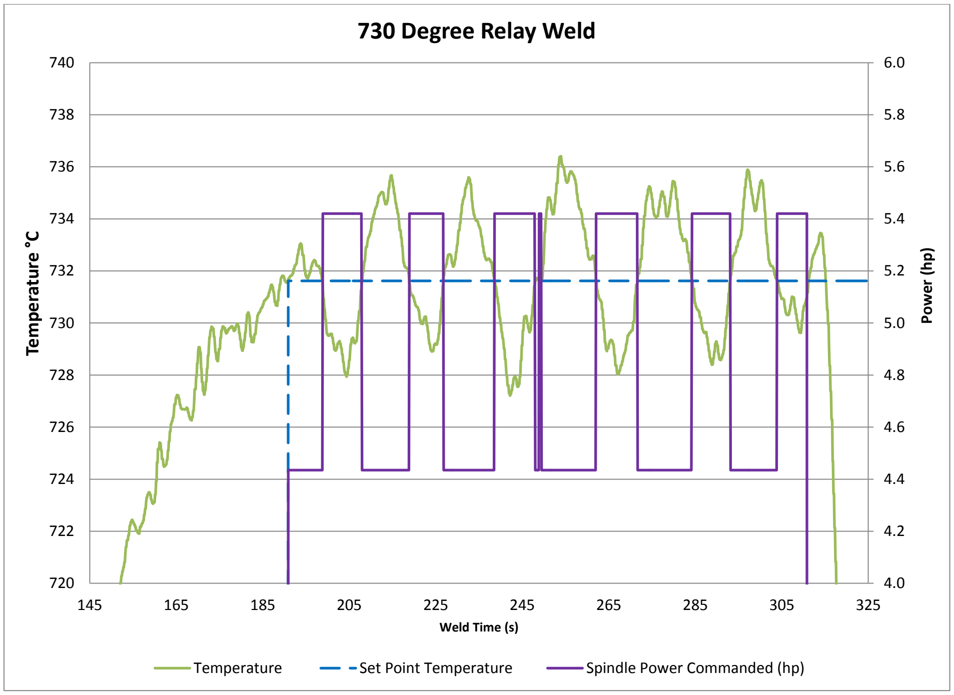

Figure B.12: 730°C steel relay weld was run with the first tool.

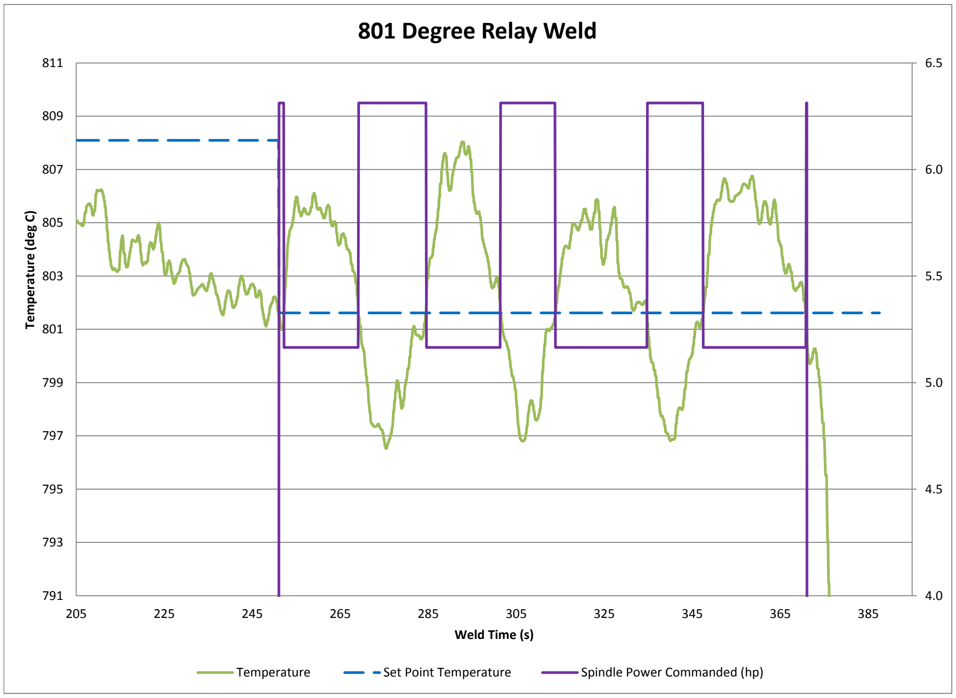

Figure B.13: 800°C steel relay weld with the first tool.

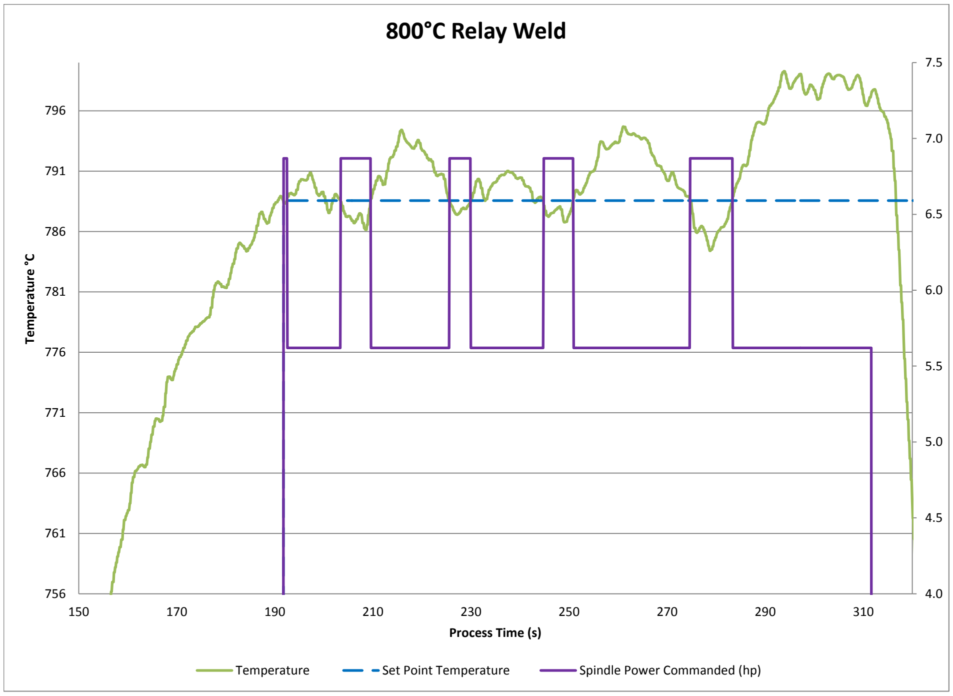

Figure B.14: 800°C steel relay weld with the second tool.

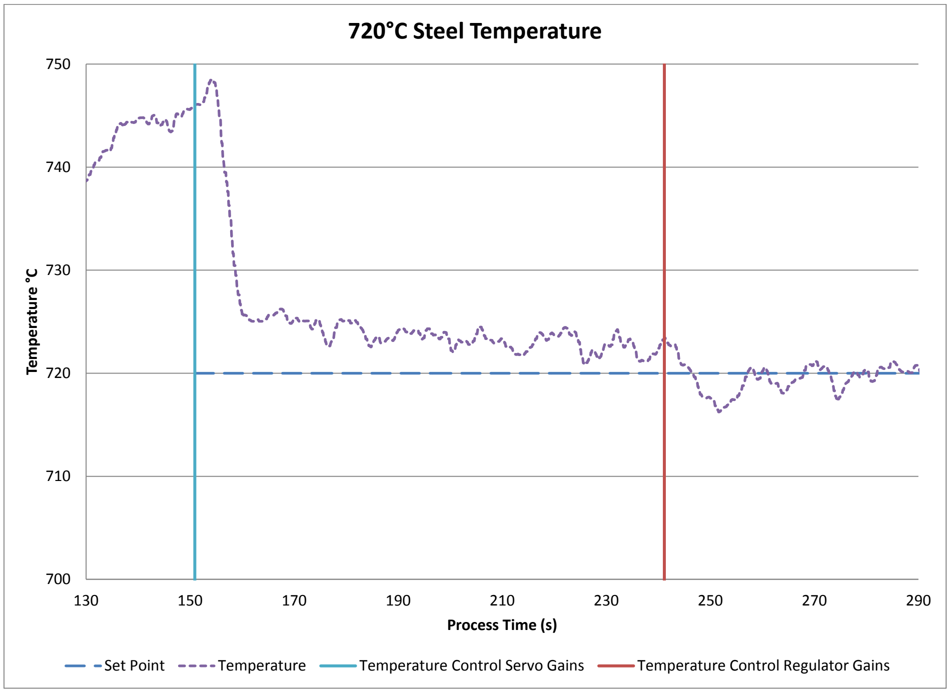

Figure B.15: 720°C steel temperature controlled weld which was run with the first PCBN tool.

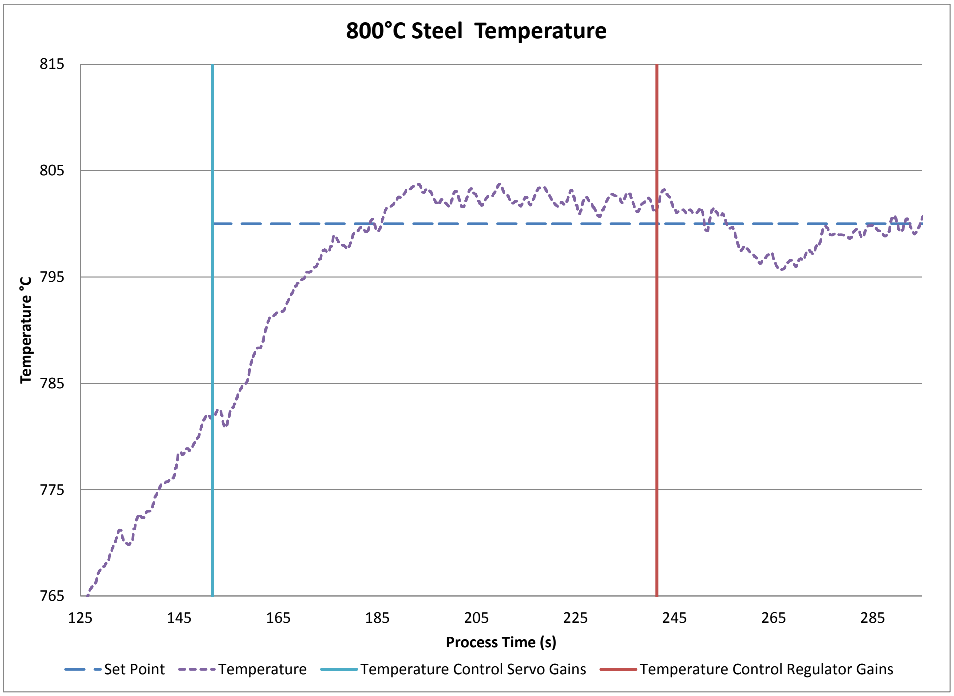

Figure B.16: 800°C steel temperature controlled weld which was run with the first PCBN tool.

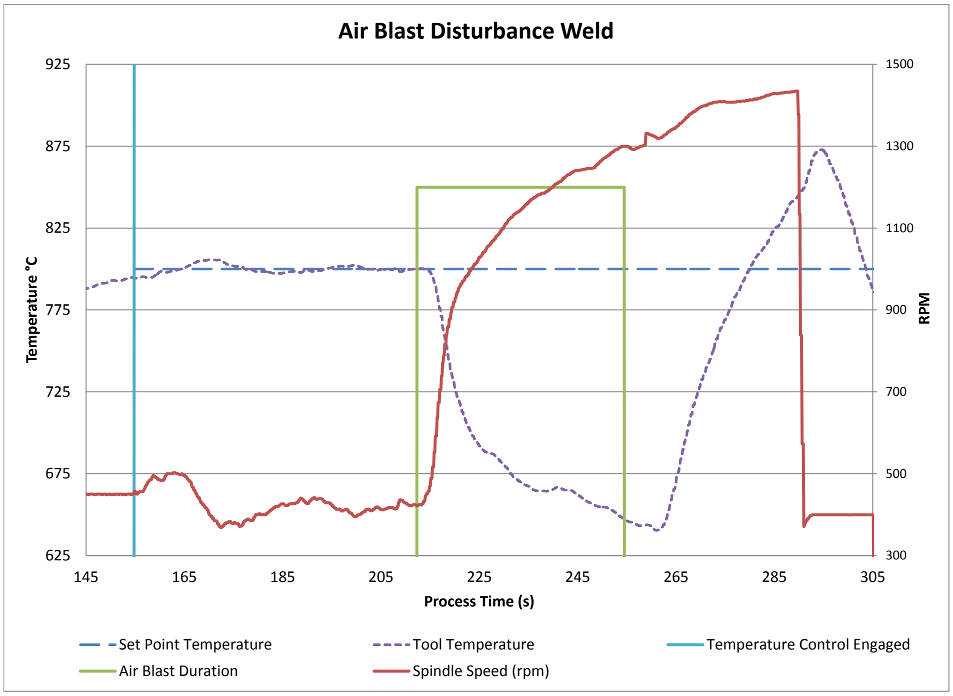

Figure B.17: Air blast disturbance welds were run in steel with the second PCBN tool. They were run at 800°C.

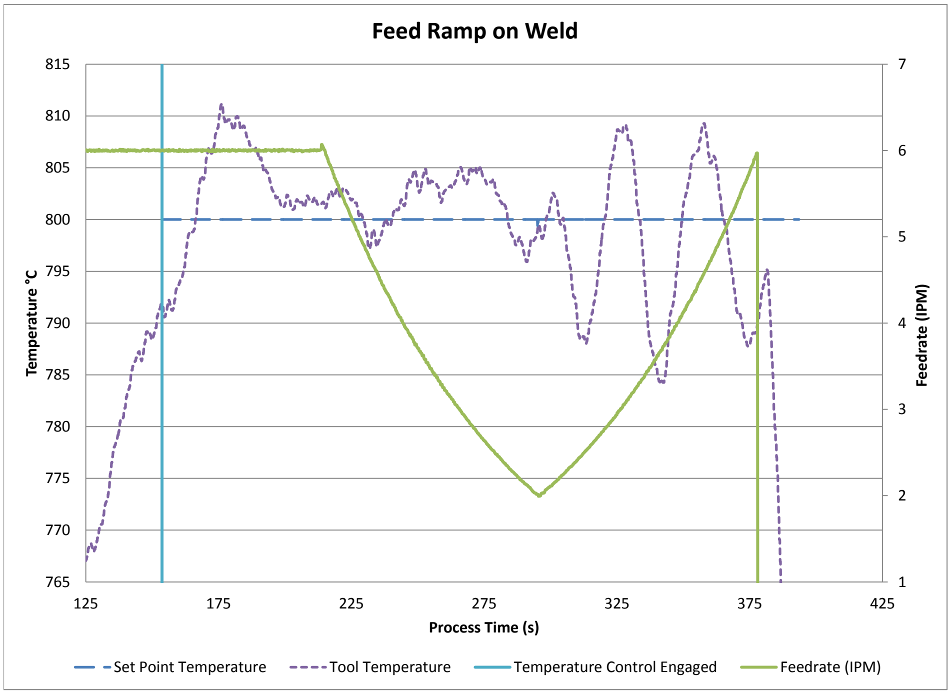

Figure B.18: Temperature controlled welds were run at 800°C in steel. During the weld, the feed rate was ramped down and back up again to simulate a geometric disturbance.