CHAPTER III

THE IDENTIFICATION OF THE KEY ENABLERS FOR FORCE CONTROL OF FRICTION STIR WELDING

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Abstract

The process requires a large axial force to be maintained on the tool. Force control is needed in robotic friction stir welding (FSW) processes to compensate for the compliant nature of robots. Without force control, welding flaws would continuously emerge as the robot repositioned its linkages to traverse the tool along the intended weld seam. Insufficient plunge depth would result and cause the welding flaws as the robot's linkages yielded from the resulting force in welding environment.

As FSW continues to emerge in manufacturing, robotic applications will be desired to establish flexible automation. The research presented here identifies the key enablers for successful and stable force control of FSW. To this end, a FSW force controller was designed and implemented on a retrofitted Milwaukee Model K milling machine. The closed loop proportional, integral plus derivative (PID) control architecture was tuned using the Ziegler-Nichols method. Welding experiments were

conducted by butt welding 0.25 inch (6.35 mm) x 1.50 inch (38.1 mm) x 8.0 inch (203.2 mm) samples of aluminum 6061 with a 0.25 inch (6.35 mm) threaded tool.

The experimental force control system was able to regulate to a desired force with a standard deviation of 129.4 Newtons. From the experiments, it was determined that tool geometry and position are important parameters influencing the performance of the force controller, and four key enablers were identified for stable force control of FSW. The most important enabler is the maintaining of the position of a portion of the tool's shoulder above the work piece surface. When the shoulder is completely submerged below the surface, an unstable system occurs. The other key enablers are a smooth motion profile, an increased lead angle, and positional constraints for the tool. These last three enablers contribute to the stability of the system by making the tool's interaction with the nonlinear welding environment less sensitive.

It is concluded that successful implementation of force control in robotic FSW systems, can be obtained by establishing and adhering to these key enablers. In addition, force control via plunge depth adjustment reduces weld flash and improves the appearance of the weld.

Introduction

Friction Stir Welding (FSW) is a solid state material joining process. The process involves plunging a rotating tool into the parent metals that define the work piece. The rotating tool consists of a shoulder and a pin (or probe) that is used to plastically deformed the parent metals and then forge them together into a single piece of material. As the tool rotates and traverses along the joint line to be welded, it shears a thin layer of material from the parent metals and then rotates the materials to the backside of the pin. While at the backside, the severely deformed materials are consolidated under the forging pressure of the shoulder. Heat generated through plastic deformation and friction softens the work piece and aids in the joining process by reducing the resulting forces.

FSW is emerging as a viable technology in the fields of manufacturing and product development. Successful applications of the joining of various alloys have made FSW an attractive technology for the aerospace and automotive industries. The current state of FSW technology restricts its usage due to process limitations, equipment requirements, capital investments and a lack of full understanding of the physical joining process.

As FSW technology began to mature during the late 1990s, robot applications became apparent. Similar to other welding technologies, the application of FSW through robotics provides a very flexible platform for automation. However, with FSW the relatively large forces present a challenge. Robots are limited by the magnitude of the load they are able to support at their face plates. In addition, their compliant nature makes FSW much more challenging. To address the compliance problem, force control has been presented as a solution. With robotic FSW the challenge is to keep the tool positioned correctly while the linkages of the robot continually reposition themselves. The motion of the linkages along with the large forces acting at the face plate results in tool positioning errors. Along with these positioning errors, large fluctuations in axial force result. These positioning errors and force fluctuations will lead to insufficient deformation, forging and consolidation of the parent metals.

Cook et al. (2004) (2003) stated force control is the key to controlling robotic FSW. They performed an in-depth study of how the axial force changes as a function of process parameters. They determined that maintaining position control of the tool relative to the work piece is too difficult, and that force control is a much more robust control strategy for robotic applications of FSW. Another conclusion drawn by their work is that the indentation characteristics of the tool, as it moves downward into the work piece, is ill behaved and could cause closed-loop instability. They note how a small amount of change in the vertical position of the tool, while in contact with the work piece, produces large changes in the axial force. The shape of this response varies under different process conditions such as rotation speed. Lastly, they note how the force tends to return to its initial value after the tool has plunged deeper into the work piece. They conclude that no significant increase in force occurs, other than the initial transient. Notice how the force spikes as a result of small step inputs. In addition notice how the force slowly subsides back near its original value prior to the increase in plunge depth.

Successful applications of robotic FSW have been documented with work by Smith (2000), Soron and Kalaykov (2006), and Zhao et al. (2007). They all developed and implemented a force control architecture using plunge depth as the controlling variable. They were able to conclude that it was feasible to implement FSW force control architectures. However, using plunge depth as the controlling variable did present several challenges. Soron and Kalaykov concluded that even with the added force control to the robotic FSW system, axial force oscillations exist when the tool makes contact with the material. They also note the penetration depth is hard to predict due to the positioning error of the robot. Zhao et al. presented a non-linear axial force controller they developed and implemented for a FSW process. They were able to experimentally characterize the static and dynamic behavior of the interaction between the FSW tool and the work piece. With this information and using an open architecture control system they were able to design a controller using Polynomial Pole Placement. Good results were obtained, but to handle the non-linear transient response when the tool's plunge depth changed, the control system had to incorporate experimentally obtained dynamic parameters. Thus, the open architecture of the control platform was needed in order to implement this force controller. Plus, the controller parameters were specific to their experimental setup.

Even with these advances the problems associated with robotic FSW remain open. As noted by Soron and Kalaykov, problems still exists with force oscillations. The highly non-linear aspect of the welding environment makes it extremely difficult to implement a robust system that maintains stability over a large range of process configurations and parameters. The papers cited above report successful implementations of robotic FSW systems, but they do not state in detail why they were successful.

The goal of this research was to build a FSW force controller and identify key enablers of the system so that efficient and successful implementations can be performed in the future. These key enablers specifically address stability issues associated with varying plunge depth. It was concluded that tool geometry and tool position relative to the work piece play an important role in maintaining stability of the system. In addition, a comparison is drawn to other force control systems that utilize plunge depth as the controlling variable. Recommendations are made regarding automatic machinery configurations.

Experimental Setup

The experiment was conducted on the FSW system at Vanderbilt University. The FSW system is a Milwaukee Model K milling machine that has been retrofitted with more advanced motors and instrumentation. The system is shown in Fig. 3.1. These retrofits were previously added to automate the system and provide a programmable platform for FSW experimentation. At the top of the control hierarchy is a master computer that enables all of the systems subcomponents such as the motor drive controllers and instrumentation. The master computer is a Dell Precision 340 that uses Microsoft Windows XP as its operating system. The welding and force control code was written in C#. A graphical user interface within the C# software allows the operator to select the desired welding parameters for the pending operation. These parameters include the FSW tool's rotation speed, traverse speed, plunge depth and weld path position.

The tool's vertical axis coincides with the milling machine worktable's vertical axis when the tool is at a zero degree tilt angle. The worktable resides on the knee that is mounted to a vertical positioning screw and secured in sliding dovetail joints. The knee travels on the screw via a gear system inside the knee. An externally mounted belt and pulley system is attached to the input shaft of the gear system. Power is provided by a Parker Compumoter KH series brushless servo motor. The servo motor is controlled by a Parker Compumotor KHX-250 servo drive that utilizes a proportional, integral plus derivative (PID) control algorithm. Command signals are sent directly from the master computer to the servo drive. Vertical position of the table is obtained from a Reinshaw linear scale that has a resolution of 10 micrometers (0.0004 inches). Position data from the sensor is feed into a sensor box were it is converted to a digital signal prior to being sent to the master computer.

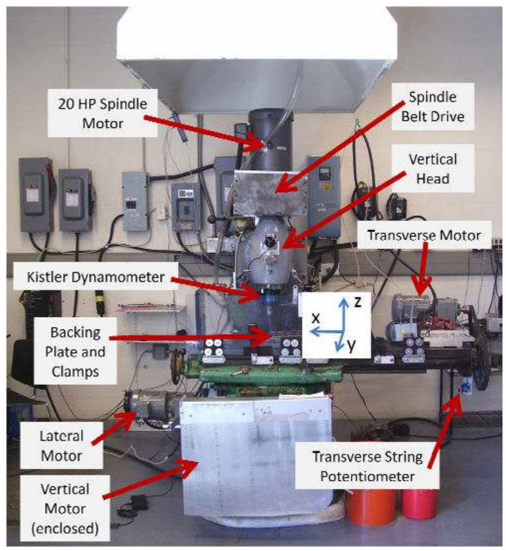

Figure 3.1: FSW machine at Vanderbilt University.

Welding force data is collected through a Kistler Rotating Cutting Force Dynamometer. The dynamometer collects x-axis force, y-axis force, z-axis force as well as the torque about the z-axis. The analog signal from the dynamometer is sent to a signal conditioning box were it is converted from an analog signal to a digital signal. Once converted the data is sent to a separate computer where the data is sorted, recorded and displayed before being sent to the master computer.

An overview of the closed loop force control system is illustrated in the control block diagram of Fig. 3.2. Within the master computer a desired z force is selected. The desired force value is subtracted from the actual z force value to obtain a force error. The force error signal is then processed in the control law. The resulting processed control signal is then multiplied by a factor of 0.09 to translate the signal from Newtons of force to a desired rate of change in the servo motor's shaft. The servo drive produces a change in the vertical position of the tool which results in a change the of z force in the welding environment. The dynamometer reads the resulting force and returns it to the master computer where it is once again compared to the reference signal.

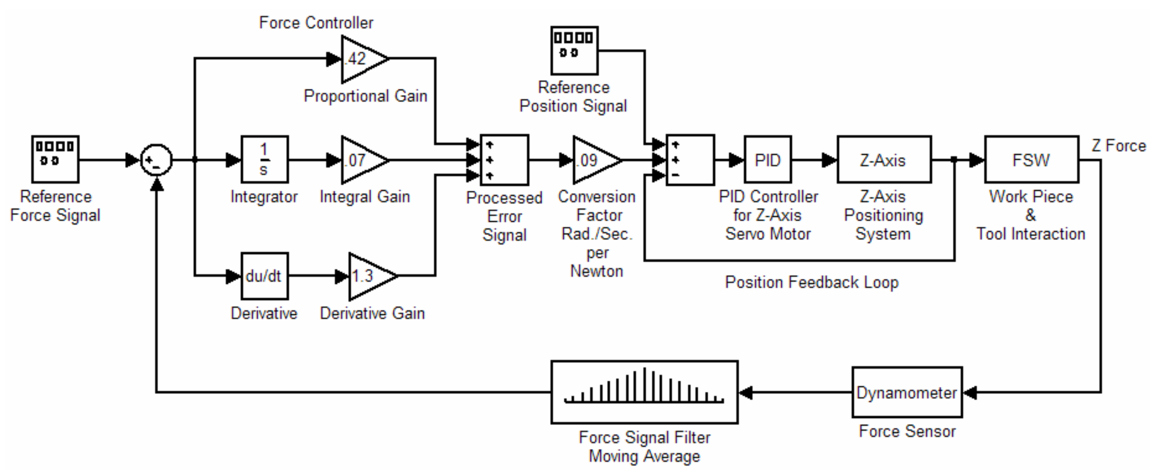

Figure 3.2: Block diagram of force control via plunge depth.

The servo motor has two modes in which it can operate. The servo motor can move its output shaft to a desired position or it can turn the output shaft at a desired speed. In addition to the mode selection, velocity and acceleration profiles were preprogrammed for complete motion control of the output shaft and the movement of the FSW tool.

The measured z force signal was very noisy. This noise makes the process of applying derivative control to the system very difficult. The noise would simply be amplified by the controller. To address this problem, a filter was implemented. The filter is a five point moving average of the z force with an interrupt frequency of 3.33 Hz. For this experimental setup these filter parameters were found to provide adequate noise reduction without adding too much phase lag in the signal.

The force control law consisted of PID control. Due to the retrofitted nature of the FSW system there are several unknown parameters that could not be accurately modeled to create a non-linear modeled based control system. For instance, the force control loop resides outside the control loop for the vertical drive system. The Parker Compumotor drive and servo motor uses its own proprietary control techniques to drive the motor. Thus, obtaining the parameters of the controller as well the physical parameters of the motor, belt drive, and power screw would require an extensive amount of testing and analysis. In addition, the time needed for signal processing and transmission through the master computer, dynamometer, sensor box and the servo would also have to be experimentally determined. With all of these variables to consider the potential performance of a model based controller might not be much better than a standard PID controller. For this study to create and investigate the performance of z axis force control via plunge depth, PID control architecture was chosen as the best option. To address the transport delay between the initiation of the control signal and the change in force, a simple delay of 1 second in the control update time was utilized. The 1 second delay allowed the FSW tool to change position and a change in z force to occur. The delay in control signal update proved to be effective without the need of adding a more complicated controls approach such as a Smith Predictor-Corrector (Ogata 2002).

To tune the PID force controller and achieve optimum control, the Ziegler-Nichols tuning method was used (Ogata 2002). The Ziegler-Nichols tuning method called for the controller to use only proportional gain while welding. While using proportion control only, a critical gain value was experimentally determined through trial and error. Over the course of several welds, the gain was steadily increased until the resulting z force achieved sustained oscillation. The sustained oscillation constituted marginally stable behavior. The resulting control gain and time period between oscillations was recorded and used to calculate PID gains for the controller. The resulting PID control law is shown in Eq. (3.1). In Eq. (3.1), K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, e is the error and u is the resulting control signal as a function of time t.

$$K_p\, e + K_i \int e + K_d\, e' = u(t) \tag{3.1}$$

For this force control research, experiments using two different FSW tools were performed. The two tools with their contrasting size and geometry provided insight into the dynamics of the FSW system. The first tool consisted of a slightly undersized 0.25 inch (6.35 mm) Trivex pin with a flat 0.625 inch (15.875 mm) diameter shoulder. The Trivex profile geometry is similar to an equilateral triangle, but with its edge surfaces slightly convex. The pin with its Trivex geometry was 0.235 inches (5.969 mm) long by 0.210 inches (5.334 mm) across its widest point. The second tool was larger in size as compared to the 0.25 inch (6.35 mm) Trivex. The second tool consisted of a 0.25 inch (6.35 mm) threaded pin. The threaded pin was 0.235 inches (5.969 mm) long with a diameter of 0.250 inches (6.35 mm) across its threads. The shoulder was of a hybrid nature. It had a flat 0.625 inch (15.875 mm) diameter shoulder that acted as the forging surface. The remaining portion of the shoulder was on a 7° taper that started at the 0.625 inch (15.875 mm) diameter point and continued to the 1.0 inch (25.4 mm) outermost diameter. The tools are shown in Fig. 3.3.

Figure 3.3: Trivex and threaded FSW tool.

Using the Ziegler-Nichols tuning method, critical gains were determined for both tools. The critical gain and period for the 0.25 inch (6.35 mm) Trivex tool was 3.5 and 13 seconds respectively. The critical gain and period for the 0.25 inch (6.35 mm) threaded tool was 4.14 and 7.5 seconds respectively. The resulting control gains are shown in Table 3.1.

Table 3.1: Plunge Depth Mode Force Control Gains.

1/4" Trivex Tool P.D Mode:		Kcr=1.0	Pcr=13	1/4" Threaded Tool P.D Mode:		Kcr=0.7	Pcr=12.5
	Kp	Ki	Kd		Kp	Ki	Kd
PID	0.6	0.2564	0.975	PID	0.42	0.0672	1.3136
P	0.5			P	0.35		
PI	0.45	0.0415		PI	0.315	0.0302	
PD	0.45		0.1578	PD	0.315		0.3

For the experiment 0.625 inch (6.35 mm) butt welding with full penetration was performed. The material used was aluminum 6061. The work piece consisted of two 0.25 inch (6.35 mm) by 1.50 inch (38.1 mm) by 8.0 inch (203.2 mm) long samples. Each weld began with the tool plunging into the metal 1.0 inch (25.4 mm) from the end of the work piece. Once the tool achieved the desired plunge depth it dwelled at that location for 5 seconds in order to soften the work piece by generating additional heat. After dwelling, the tool began to traverse forward at 6 inches per minute (IPM) (152.4 mm per min.). After traversing 1 inch (25.4 mm) the force controller was engaged. The force controller was operating in a regulation mode, meaning whatever the z force was at the time of engagement, was the selected desired force. The system operated under force control mode until it reached 1 inch (25.4 mm) from the end of the 8 inch (203.2 mm) work piece. Thus 5 inches (127.0 mm) of welding was conducted each time under force control. For many of the welds a step input in desired force occurred after 2 inches (50.8 mm) of regulation. Each step input was of 1000 Newtons in magnitudes. For every weld made, the tool's shoulder was initially plunged between 0.000 – 0.002 inches (0.0508 mm) below the surface and the tool's rotation rate was maintained at a constant 1400 revolutions per minute (RPM).

To provide a base line of the welding environment, a weld was made without any force control using the 0.25 inch (6.35 mm) Trivex tool. The results are shown in Fig. 3.4. The resulting force during the initial tool plunge into the work piece is identified on the figure as the pin plunge and shoulder plunge regions. After the tool has plunged and dwelled for 5 seconds, the forward motion of the tool begins. This point is easily identified as the sharp increase in force after the shoulder plunge and dwell period. After 1.0 inch (25.4 mm) of forward travel the force controller is normally engaged at this point. However, for this base line sample the force controller is not engaged, but the force occurring at the engagement point is displayed as a desired force reference. From the base line sample it can clearly be seen that the z force continues to increase about two thirds of the distance across the weld seam. The increase is due to the tool moving into un-welded and colder material. This also indicates the welding process has not yet reached a steady state.

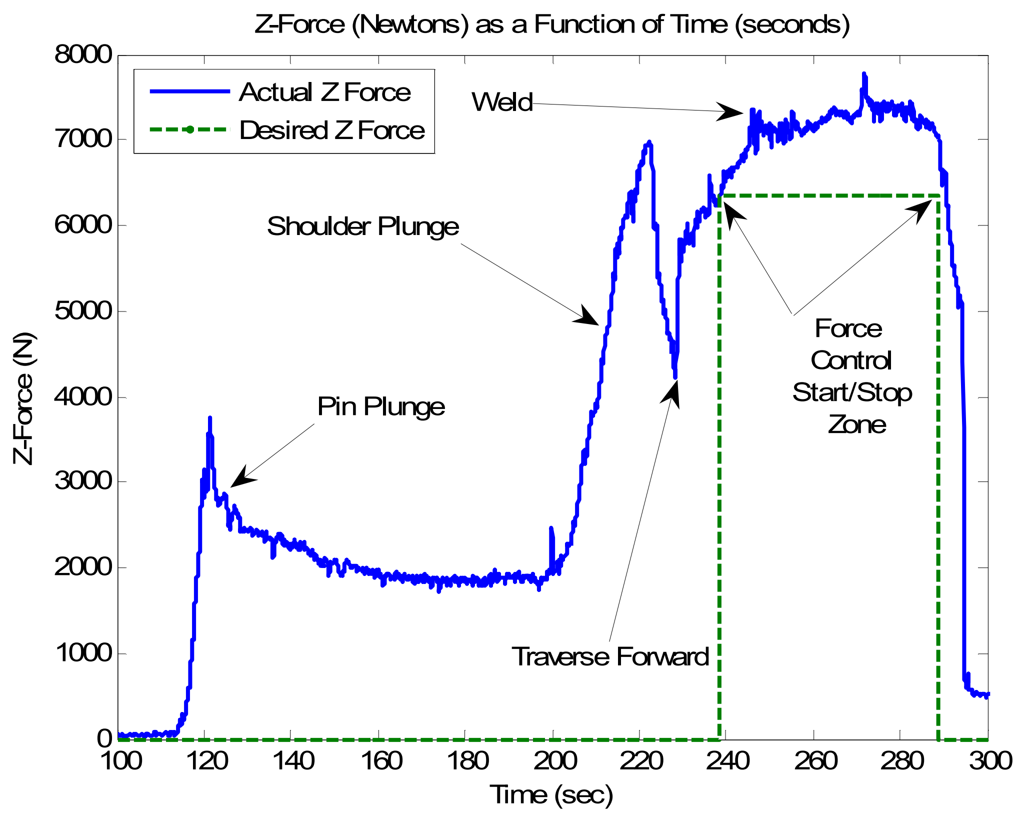

Figure 3.4: Weld sample with no force control.

Results and Discussion

Initial observation of the system's performance leads to the identification of the important configurations necessary for stable control. The highly nonlinear welding environment and the tight coupling of the axial force to the process parameters as well as the thermal conditions dictate the need for robustness. To achieve this robustness, specific process configurations must be realized and correctly implemented. These configurations include the tool's position relative to the work piece, the geometry of the tool and its dynamic characteristics. Without properly addressing these issues, instability will result. The parameters were identified through numerous tests and analytical reasoning. The requirement to establish these conditions holds true for both robotic and machine tool applications.

As the tool was either plunged further or retracted slightly from the work piece a rather large transient force was observed. This force response can be characterized as viscous in nature. In other words it was proportional to the velocity of the FSW tool. Since the welding environment is rather stiff, any movement in the tool will generate a large change in force. As the tool began to move, the force quickly increased (or decreased) causing the error signal in the force control to quickly reach a value of zero and thus stopping further motion of the tool. However once the force was achieved, it began to dissipate back to its original value. This was true for both plunging and retracting motions. These transient forces proved to be taxing on the control system. The controller was constantly starting and stopping the motor. More importantly the generated force change was a result of the tool's velocity and not its position relative to the work piece.

Smother tool motion was found to reduce the transient effect. Although the sudden change in force can not be eliminated, it can be reduced in magnitude. A reduction in magnitude produces a feedback signal to the force controller that is more representative of the tool depth into the work piece than its velocity. Tool plunge depth is more important than vertical velocity in producing a quality weld. The tool's shoulder must be in contact with the work piece in order for the plasticized material to be forged together on the backside of the pin. During the early phases of force controlled welding, it was observed that an adequate z force can be generated while an inadequate amount of shoulder contact is present. This occurs when the shoulder disengages from the work piece and the z force does not drop significantly due to the highly nonlinear environment. When this happened the force sensor could not distinguish between a force being applied on the pin and the force on the shoulder.

With a reduction in the transient force, the force controller can more efficiently use the z axis servo motor. The change in force becomes more of a function of tool position and less of a function of tool velocity. Since the force is more indicative of position, the z axis motor is not as taxed. The motor does not undergo as many on - off cycles to drive the tool to its required position.

The z axis servo motor on the FSW system at Vanderbilt University has two modes of operation. One is a discrete mode and the other is a continuous mode. The discrete mode turns the motor's shaft to a desired position under a desired acceleration and velocity. In the continuous mode the shaft turns at a desired velocity until it receives a stop command. In both modes, motion profiles establishing the acceleration and velocity are entered as part of the input command.

Due to the highly nonlinear welding environment, the continuous mode was found to produce better results. To operate over a wide range of parameters, the discrete mode required the force controller to know how much to adjust the plunge depth. Although the plunge depth will change proportionally to the force error, changing thermal conditions within the work piece will change the amount of force produced by a unit change in plunge depth. Thus a tuned controller would have a narrow range of process parameters for optimum performance. The amount of time to eliminate the force error will take longer due to the nature of the incremental changes in plunge depth. By using the continuous mode, the force controller has a much larger range for optimum performance. In the continuous mode the servo motor adjusts the plunge depth until the force controller tells it to stop. It is told to stop when the force error has returned to zero. By using the continuous mode of operation, much faster response time in eliminating force error is experienced.

The motion profile shown in Fig. 3.5 was found to work well for the FSW force control system established at Vanderbilt University. The magnitude of the acceleration and velocity is scaled to the size of the processed error signal. The amount of time for the acceleration and deceleration was preset at 0.2 seconds. This value was found to be adequate for this system. When selecting the acceleration time for future systems, a compromise must be made between response time and reduction of the transient force response. A longer acceleration will lead to a slower response and a larger amount of error. Along with the acceleration, a long deceleration will cause a force overshoot. In contrast, a large change in acceleration over a short period of time will cause a jerk action, which will result in a larger transient force. The key enabler is to create smooth motion while maintaining an adequate response time.

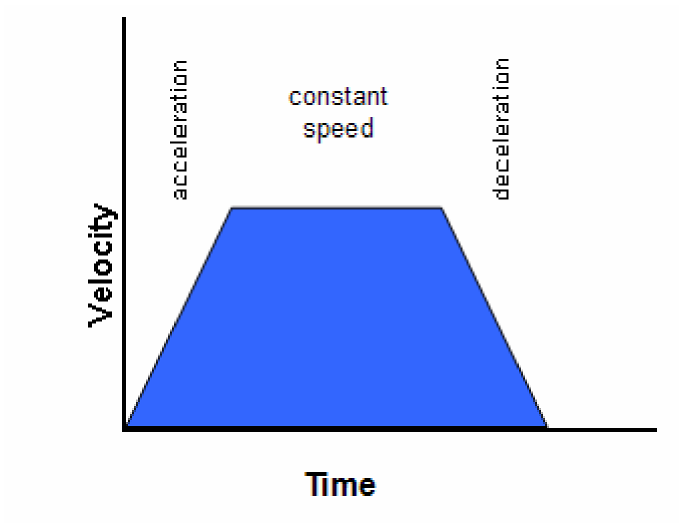

Figure 3.5: Servo motor motion profile.

As mentioned above, it was observed while welding under force control, the shoulder disengaging from the work piece while the axial force still remained near a constant value. This is possible because once the shoulder is removed from the work piece, less heat is generated in the welding environment. With less heat, the work piece becomes stiffer. With just the pin plunged into the stiffer work piece, the same amount of force can result as when the shoulder is plunged into a softer work piece. A method to prevent this control issue is to constrain the plunge depth.

Adding constrains to the plunge depth induces an element of positional control into the system. This is easily accomplished by monitoring the position of the tool relative to the work piece and then restricting its motion from going beyond the constraint boundaries. Adding constraints does not completely prevent the shoulder from disengaging from the work piece in all cases. When the constraint boundary is established it must be at the maximum height of the work piece. The maximum height might not always be accurately known because of material thickness variation. In addition, when the work piece's thickness is at its minimum condition, it still will be possible for the shoulder to disengage from the work piece.

Only a very small amount of plunge depth is needed to produce a quality weld. Hence there is a very narrow range of vertical travel between a quality weld and a no weld condition. Excellent welds were produced with plunge depths of only 0.000 to 0.002 inches (0.000 to 0.0508 mm). These shallow plunge depths were possible due to the initial plunge of the tool into the work piece. As the tool plunged, material was extruded upward along the pin and onto the surface of the shoulder, thereby creating a layer of material between the shoulder and the work piece prior to the backside of the shoulder reaching the nominal height of the work piece. Deeper plunge depths can be obtained but undesirable weld flash is generated. The presence of weld flash means less material is in the weld joint which reduces its load bearing capability. In addition, if the weld seam needs to be cosmetically pleasing, some type of flash removal operation must be preformed after welding. Thus careful planning and control of the plunge depth will make a manufacturing operation more efficient.

Constraining the maximum amount of plunge depth is also beneficial. It was also observed than during very hot welding conditions the tool would continue to plunge into the work piece without a significant amount of force increase. If the tool continues to plunge into the work piece without an increase in force two major problems will arise.

The first problem is that the tool might collide with the backing anvil. Under ideal conditions the pin must be a few thousands of an inch above the backing anvil. With the pin rotating, material just below its bottom surface undergoes plastic deformation and forging. It is not necessary for the tool to fully penetrate the work piece in order to produce full penetration welds. If the tool fully penetrates, some bonding between the work piece and the backing anvil would likely occur. Obviously, this is an undesirable condition that must be avoided. If the pin did collide with the backing anvil, the tool would encounter increases in load, and could fracture and damage the fixture. This is another undesirable condition that must be avoided.

The second major problem that occurs without a constraint for maximum plunge depth is an unstable condition will evolve once the entire shoulder is submerged below the surface of the work piece. For force control via plunge depth to work, there must be a change in force when the plunge depth is changed. It was discovered that the z force is not necessarily a function of plunge depth. It is more a function of the amount of tool surface area in contact with the work piece. As a tool is plunged into the work piece, more of its shoulder's surface area comes into contact with the work piece. This assumes that the tool is on a lead angle, or the shoulder is tapered, which is typical of most applications. With more surface area in contact with the work piece, more force occurs. Once the shoulder is completely submerged below the surface a completely different set of dynamics arise. As the tool continues to travel deeper, there is not a change in the amount of shoulder surface area in contact with the work piece. Without a change in surface area, there is not a change in force that can be related to plunge depth. The z force overwhelming becomes a function of plunge depth velocity rather than plunge depth. When the shoulder is submerged below the surface, the slightest movement of the tool in the vertical direction produces a spike in the z force. The force continues to increase or decrease until the force error is eliminated. For our configuration, it only required a slight amount of tool movement for this to occur. However, as soon as the motion stopped, the force quickly returned to near its original value. It is reasonable to conclude that the transient nature of the force is due to material being squeezed out from underneath the tool when the tool is plunged deeper into the work piece. The opposite condition occurs when the tool's plunge depth is reduced. As the tool is retracted, the material underneath the tool relaxes due to its elastic property. The relaxation of the material exerts less force on the tool. However, when a portion of the tool's shoulder is above the work piece's surface, the change in force due to the change in tool surface area contact with the work piece dominates the process. A much larger value of force occurs when more surface area comes into contact with the work piece than that which occurs when material is squeezed from beneath the tool. This is evident by the reduction in the transient force when part of the tool's shoulder is above the work piece's surface. Since a very large change in force occurs when there is a change in the amount of tool surface area exposed to the work piece, only a small amount of tool movement is needed to generate the change in force. A small amount of tool movement in conjunction with smooth motion minimizes the transient spike in z force and thus adds stability to the force controller.

Of course there is still a small relation between tool depth and z force, once the tool's shoulder is submerged below the surface. However, it requires such a large amount of tool movement, it becomes impractical due to the large amount of generated weld flash. As an example, when the plunge depth was started at 0.009 inches (0.2286 mm) and the tool began to traverse forward there was a natural increase in z force due to the tool moving into a colder welding environment. As would be expected the force controller tried to lower the z force back to the desired value by reducing the plunge depth. As soon as the controller adjusted the plunge depth the force quickly dropped in value and the controller stopped the motion of the tool. Soon after that, the force returned to its prior value. The process continuously repeated itself. The force varied up and down with virtually no sense of control being realized. After a few minutes the tool had traveled the 0.009 inches (0.2286 mm) to the work piece's surface. Once at the surface the amount of the tool shoulder's surface area exposed to the work piece changed with each vertical motion. At that point the transient force spikes subsided and a sense of force control emerged. The desired z force was able to be achieved and maintained once the tool's shoulder was at the surface.

Tool geometry was found to play an important role in the dynamic behavior of FSW under force control. As mention above, it is vital for a portion of the tool's shoulder to stay above the work piece's surface. It was discovered through the welding experiments that different tool geometries and configurations affect the sensitivity of the force controller. For instance the 0.25 inch (6.35 mm) Trivex tool could be configured to create an extremely sensitive condition whereby the force controller would become unstable or it could be configured so as to provide a robust and stable force control platform. This was done simply by changing the lead angle of the tool.

As noted earlier the 0.25 inch (6.35 mm) Trivex tool had a flat shoulder. When the tool was at a 0° lead angle an unstable situation occurred. Any change to the plunge depth by the force controller did not produce a lasting change in z force due to a change in shoulder surface area in contact with the work piece. The unstable situation emerged were the z force oscillated due to the transient response.

When the tool was placed at a 1° lead angle, the process became less sensitive and a stable condition emerged. As the tool's plunge depth changed, so did the amount of surface area in contact with the work piece. With the tool being on an angle, only a portion of the shoulder was below the surface. Thus, the tool had a wider range of plunge depths it could achieve without the controller becoming unstable. Using trigonometry, a range of plunge depths can be estimated. With a 0.625 inch (15.875 mm) diameter shoulder positioned at a 1° lead angle, the tool had a plunge depth range of 0.011 inches (0.2794 mm).

The range of plunge depths can be enlarged by increasing the lead angle. This was validated by welding with different lead angles. When the 0.25 inch (6.35 mm) Trivex tool was at a 1° lead angle, a 1000 N step increase in force could not be obtained. The system would simply go unstable as it tried to achieve the desired increase in force. However, when the tool was set to 2°, no stability issues arose and the force controller was able to achieve the desired increase.

This phenomenon can be expressed mathematically by analyzing the surface area of the tool's shoulder in contact with the work piece and differentiating with respect to the plunge depth variable. During stable operating conditions, only a portion of the shoulder area is in contact with the work piece. Since the tool is on a lead angle, the further the tool is plunged into the work piece the greater the amount of surface area in contact with the work piece. The resulting amount of axial force is proportional to the amount of shoulder area in contact with the work piece, assuming constant process parameters and thermal conditions.

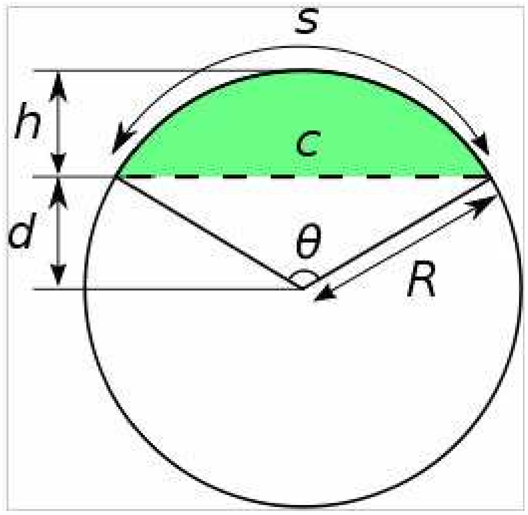

Figure 3.6: Estimated work piece contact area under a flat shoulder.

The area of shoulder contact can be estimated as a circular segment. Figure 3.6 is an illustration of the surface area of a flat shouldered tool. The green colored area labeled c represents the area in contact with the work piece. The reduction in shoulder surface area due to the pin is ignored for simplicity.

The area of contact c can be estimated by using Eq. (3.2). The variable R is the tool's shoulder radius and the angle θ is defined in Fig. 3.6 and Eq. (3.3). As the tool is plunged further into the work piece, the contact area c, increases as well. Once the shoulder is fully submerged below the surface the variable h becomes twice the radius R and Eq. (3.2) becomes the area of a circle (area = πR^2).

$$c = \left[\frac{R^2(\theta - \sin\theta)}{2}\right] \tag{3.2}$$

$$\theta = 2\cos^{-1}\left[\frac{R-h}{R}\right] \tag{3.3}$$

$$\frac{dc}{dh} = \frac{1}{2}R^2\left[\frac{2}{R\left(1 - \frac{(R-h)^2}{R^2}\right)^{1/2}} - \frac{2\cos\left[2\cos^{-1}\left(\frac{R-h}{R}\right)\right]}{R\left(1 - \frac{(R-h)^2}{R^2}\right)^{1/2}}\right] \tag{3.4}$$

$$h = \frac{\text{Plunge Depth}}{\sin\alpha} \tag{3.5}$$

By differentiating Eq. (3.2) with respect to the variable h and then substituting in the plunge depth we can determine the rate of change in area with respect to the plunge depth. Eq. (3.4) and Eq. (3.5) defines this change. Since the tool is on a lead angle α, the variable h is not the plunge depth. The plunge depth is related to the variable h as defined in Eq. (3.5).

Upon examination of Eq. (3.4) and Eq. (3.5), the force controller's sensitivity due to the tool's lead angle and plunge depth can be defined. Recalling from the text above the FSW force controller experienced instability when the tool was positioned at a 0° lead angle.

This can be explained by substituting $\alpha = 0°$ into Eq. (3.5) and then inserting Eq. (3.5) into Eq. (3.4). The resulting value for dc/dh cannot be defined. Any change in plunge depth will not change the amount of area in contact with the work piece. However, when α is a non zero value, Eq. (3.5) can be defined.

Figure 3.7 shows the resulting rate of change of area for flat 0.625 inch (15.875 mm) diameter shoulder as a function of plunge depth for different lead angles. It clearly can be seen that a wider range of plunge depths will emerge as the tool's lead angle is increased. A wider range of plunge depths means the force controller is less sensitive and more likely to remain stable. The data shows that a tool on a 1° lead angle is three times more sensitive than a tool on a 3° lead angle. With a 1° lead angle, the plunge depth can change approximately 0.011 inches (0.2794 mm) while a tool on a 3° lead angle can change 0.033 inches (0.8382 mm). The sensitivity can also be thought of as the resolution of the force controller. With a wider range of plunge depths, a more precise force value can be obtained. However with a smaller range of plunge depths, the resolution of the force controller will be diminished.

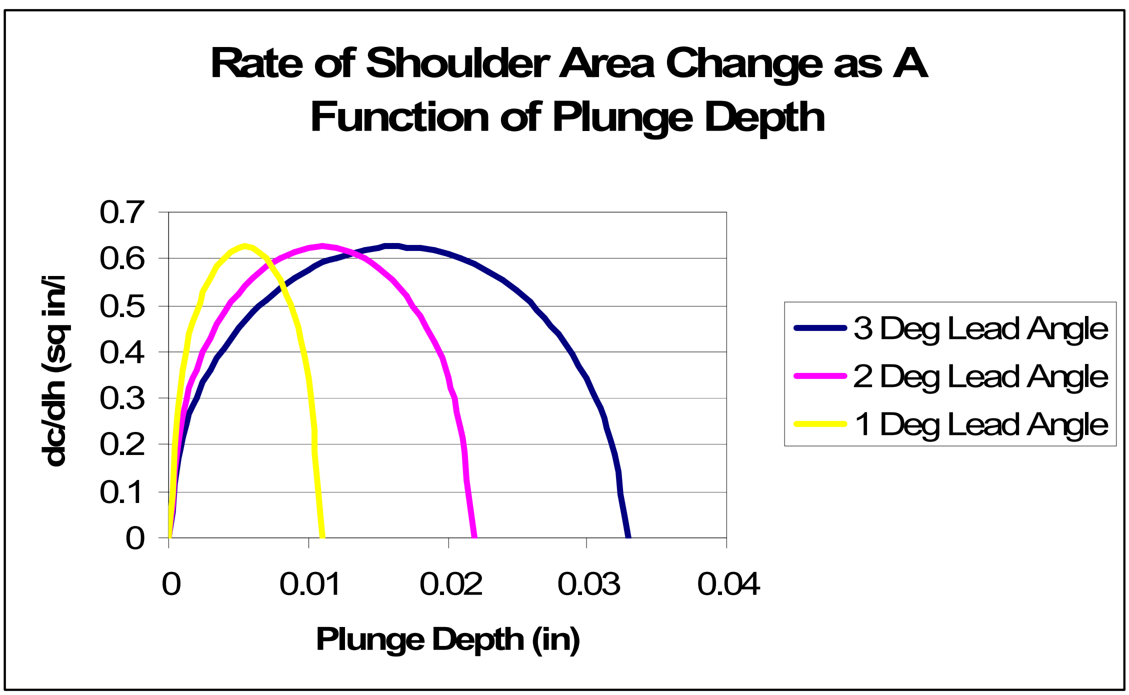

Figure 3.7: Sensitivity due to lead angle and plunge depth.

It is worth mentioning that the plunge depths used in these calculations are not practical. A plunge depth of several thousands of an inch will generate significant weld flash. The plunge depths used for these calculations assume that no material will be extruded up the side of the pin during the welding operations. This is not observed. Material on the front side of the pin does move upward to the surface and comes into contact with the shoulder. This material covers the surface of the shoulder and thus reduces the range of stable plunge depths. In reality, one could not plunge the 0.25 inch (6.35 mm) FSW tool used in these experiments 0.011 inches (0.2794 mm) and expect stable conditions at a lead angle of 1°. However, the principle outlined above remains true with respect to the relationship between sensitivity, tool geometry and lead angle.

To increase the range of stability while using a flat shoulder tool, a tapered surface near the outer region diameter of the 0.25 inch (6.35 mm) threaded tool was created and utilized for these welding experiments. The flat shoulder was found to provide a good forging environment on the backside of the pin while the tapered surface was found to extend the range of stable plunge depths. A finite element model of the tool is shown in Fig. 3.8. The tapered surface enabled the force controller to sense a large change in the material's surface and then adjust the plunge depth accordingly as the tool traversed across the work piece. These changes included 1 mm (0.03937 in.) step increases and decreases.

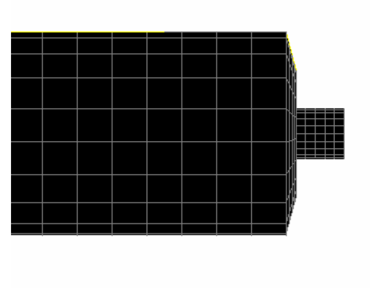

Figure 3.8: ¼ inch FSW tool with a flat and a tapered shoulder.

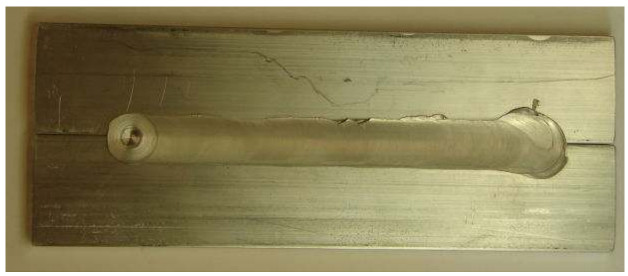

Figure 3.9: Welded sample.

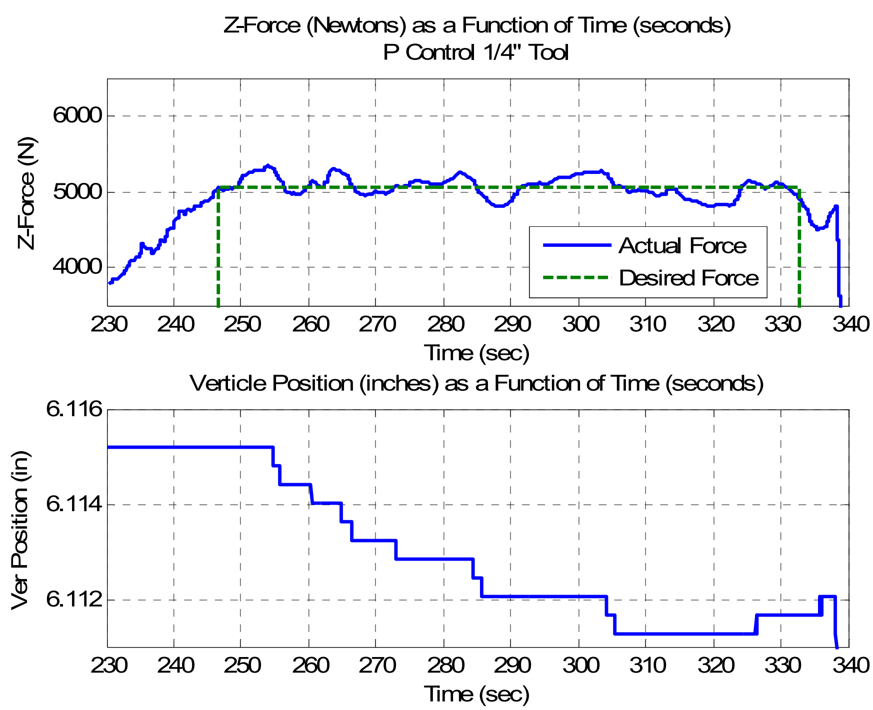

Figure 3.10: Regulation of z force, with the Trivex tool.

The force control results from using the aforementioned conditions are shown in Fig. 3.10 through Fig. 3.16 and a picture of a completed weld is shown in Fig. 3.9. Figure 3.10 shows the resulting z force and worktable position while the force controller was operating in a regulation mode under proportional control. The 0.25 inch (6.35 mm) Trivex tool described in the experimental setup was used. The force control was started at approximately 247 seconds and stopped at approximately 333 seconds as indicated by the desired force.

Statistical analysis shows the force controller performed well. The controller produced a mean force of 5067 Newtons as compared to a desired force of 5051 Newtons. The maximum value obtained was 5341 Newtons while the minimum value was 4802 Newtons. This created a range of 538.5 Newtons and median force value of 5068 Newtons. The standard deviation was 130.2 Newtons.

Figure 3.11 shows the results using the 0.25 inch (6.35 mm) threaded tool. Once again the force controller was using proportional control and operating in a regulation mode. The 0.25 inch (6.35 mm) threaded tool was slightly larger than the Trivex tool and thus a larger z force was experienced. However the controller still obtained the same level of acceptable performance as indicated from the statistical data.

The mean force was 6090 Newtons as compared to a desired force of 5942 Newtons. The standard deviation was 129.4 Newtons. The maximum force was 6432 Newtons, while the minimum value was 5829 Newtons. The median was 6077 Newtons with a range of 603.2 Newtons.

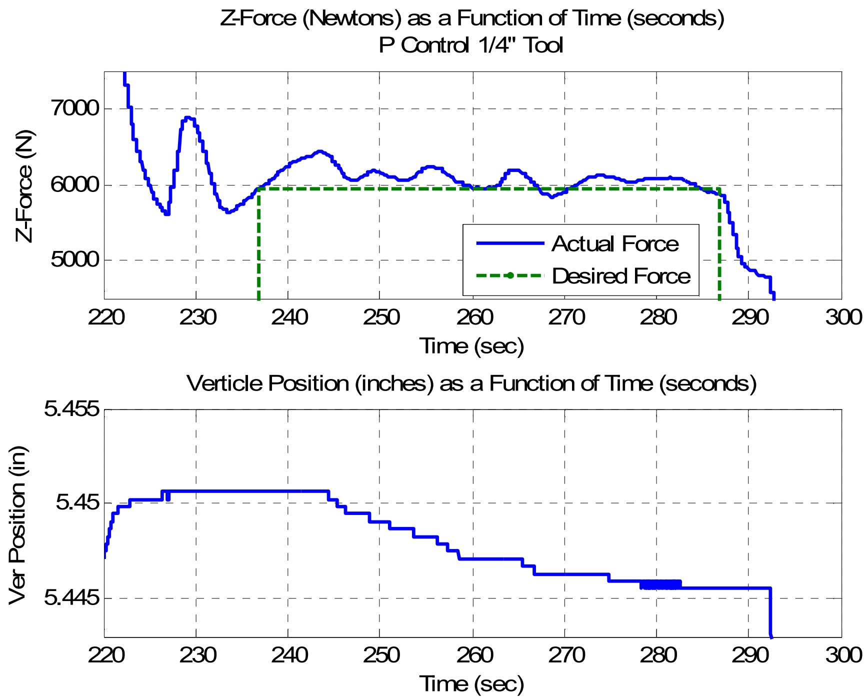

Figure 3.11: Regulation of z force, with the threaded tool.

These results are similar to results reported by Soron and Kalaykov (2006). With plunge depth as the controlling variable they were able to regulate to a desired z force with a standard deviation of 152 Newtons. Their published results were for straight line butt welding of 3 mm thick plates of aluminum using an ABB IRB7600-500 robot.

Upon examination of the results in Fig. 3.10 and Fig. 3.11, a few points can be noted. The smooth motion of the worktable enables the force controller's stability by preventing sudden spikes in force. Behavior similar to what was reported by Cook et al. [1] does not appear while the system is under force control. Sudden and abrupt movement causes the transient response observed in those experiments. However, with the implemented trapezoidal motion profile, such movements are prevented. The much more controllable and desirable condition results when smooth motion is employed.

A drawback to the smooth motion is the response time of the controller. The delayed response is amplified by backlash in the machine tool. The problem appears when the motor has to reverse direction. This is clearly evident at the beginning of the force control region in Fig. 3.11. As the FSW tool is traversing forward at the beginning of the weld it experiences a stiffer welding environment. The force controller compensates for this change by reducing the plunge depth from its initial value. The motor has to overcome the backlash in the machine tool's gearing before any movement is experience at the point of welding. Notice the delayed response at the beginning of the weld in Fig. 3.10 and Fig. 3.11. The combination of the backlash and smooth motion creates a longer response than when compared to the other adjustments made later as the tool traversed along the weld seam. This delayed response limits the bandwidth capability of the force controller. High frequency disturbances such as would be encountered over a very rough work piece surface could not be compensated for unless the traverse speed of the tool was reduced. With a reduced tool speed, the force controller and servo motor would have time to regulate the force error back to zero. This emphasizes the need to carefully select a traverse speed that is compatible with the response time of system under force control.

It is also worth noting the small amount of change needed in the plunge depth to maintain the z force over the length of the weld seam. Notice that only approximately 0.005 inches (0.127 mm) of adjustment was needed. Most of this adjustment occurred in the first half of the weld cycle due to the tool moving into a colder welding environment which resulted in stiffer material condition. The 0.005 inches (0.127 mm) of plunge depth adjustment is within the predicted adjustment range of the tool at a 1° lead angle. If there was not a lead angle, the force controller would have gone unstable.

Figure 3.12 through Fig. 3.14 shows the force controller response to step inputs. As noted previously it was determined that the force controller could not provide a 1000 Newton step increase in force while utilizing the 0.25 inch (6.35 mm) Trivex tool at a 1° lead angle. Thus for the step inputs experiments, the 0.25 inch (6.35 mm) thread tool modeled in Fig. 3.8 was used. The tapered surface of the shoulder allowed for a much wider range of plunge depths.

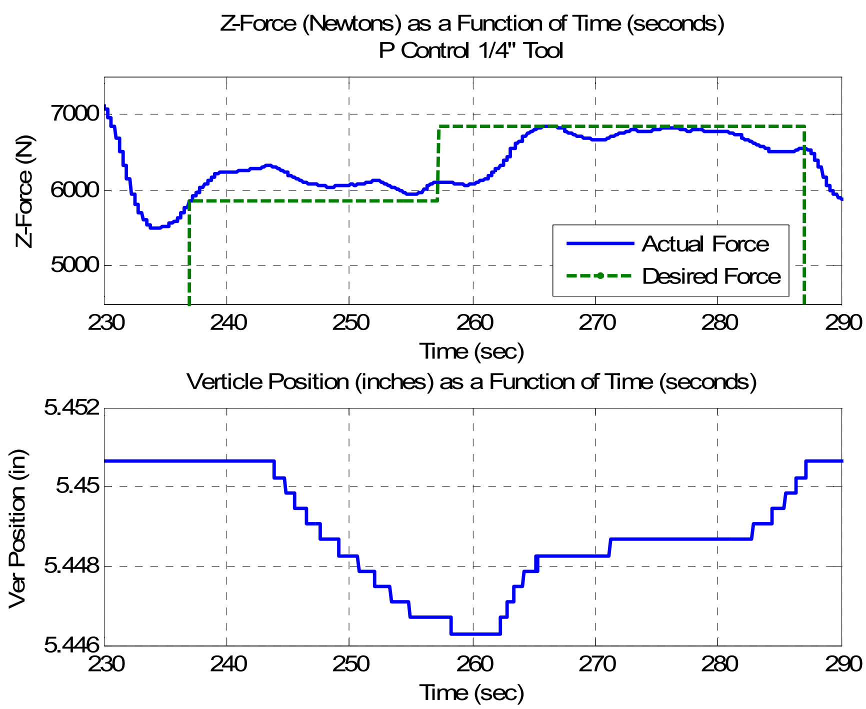

Figure 3.12: P control of step input.

Figure 3.12 shows the results of a 1000 Newton step while under proportional control. The results shown illustrate some of the nonlinear aspects of the force controlled