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Integrated Ball-Screw Based Upset Process for Index Head Rivets Used in Wing Panel Assembly

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ABSTRACT

A new high speed forming process for fatigue rated index head rivets used in wing panel assembly using ball-screw based servo squeeze actuation has been developed. The new process is achieved using a combination of force and position control and is capable of forming to 40,000 lbs at rates of up to 200,000 lbs/second whilst holding the part location to within +/− 10 thousandths of an inch.

Multi-axis riveting machines often have positioning axes that are also used for fastener upset. It is often the case that while a CNC is used for positioning control, another secondary controller is used to perform the fastener upset. In the new process, it has been possible to combine the control of the upset process with the machine CNC, thus eliminating any separate controllers. The fastener upset force profile is controlled throughout the forming of the rivet by using a closed loop force control system that has a load cell mounted directly behind the stringer side forming tool.

Panel assembly where the components are not pre-tacked is referred to as a 'one-up' process. This process requires that aircraft parts be rigidly and precisely fixtured, and that the fastening processes do not result in excessive part motion. The recently developed riveting process uses a separate position control loop and a position sensor to hold the location of the panel during rivet squeeze to within +/− 0.010″.

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INTRODUCTION

A high speed rivet upset process has been developed to support the requirements of a new one-up wing panel manufacturing cell. The new all-electric process replaces an existing hydraulic process, whilst also supporting the transition from 2024 aluminum alloy rivets to 7050 aluminum alloy. The development of the new process was largely driven by two requirements. Firstly, rivet interference and fatigue life of the fastened joint had to meet strict requirements. Secondly the one-up nature of the manufacturing process necessitates rigid clamping of aircraft parts in a fixture which meant in turn that the riveting cycle had to have near zero aircraft part motion during the upset process. The new process can be distinguished from existing published 'no-wink' processes(1) in that it is designed for index-head rivet upset using servo motor actuation.

The overall architecture of the fastening cycle will be documented in this paper, focusing on design elements of the process that are considered to be novel in the field. The different stages of the rivet forming process will be discussed, and an explanation of the findings into how varying different parts of the upset changed the interference pattern of the final riveted joint. As part of the effort to meet the riveted joint specification, and to improve overall cycle time, a significant focus of the development effort was paid to speeding up and improving efficiency of the fastening process. This paper discusses those efforts and also the technical challenges associated with high speed riveting and how they were overcome.

One-up assembly (where the aircraft parts are not pre-tacked together) requires that aircraft parts are rigidly held in an assembly fixture to maintain the configuration and shape of the finished product. This presents challenges for the design of the fastening process since traditional single sided rivet upset results in motion of the part as the rivet forms. The technical requirements of one-up assembly riveting, the design of the upset system and the principles of the control architecture and the performance of the actual system are included in this work.

MECHANICAL UPSET ARRANGEMENT

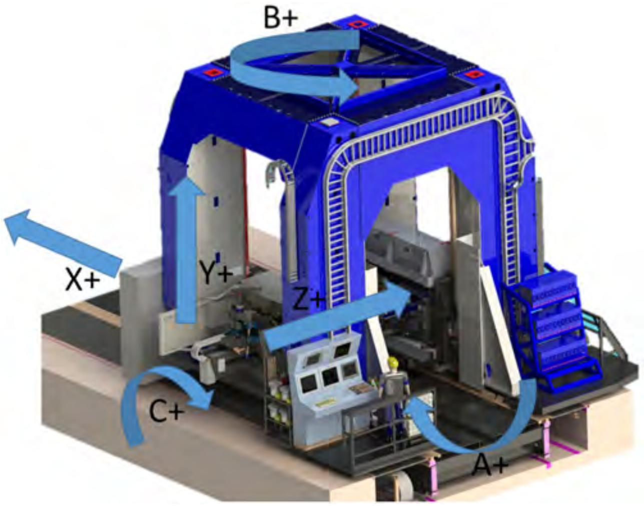

Figure 1. Vertical fastening machine overall arrangement.

The newly developed rivet upset process uses a multi-axis servo driven arrangement for fastener forming. The same axes used in machine positioning also serve as the fastener forming axes. Figure 1 shows the overall vertical panel assembly machine arrangement(2). Figure 2 shows the upset axis arrangement.

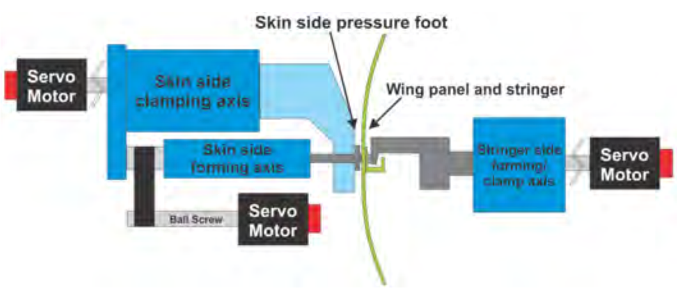

Figure 2. Mechanical upset arrangement.

Upset is primarily achieved by motion on the stringer side of the machine. However, servo motors controlling the skin side clamping head, and the skin side upset axis also move during fastener forming in order to control aircraft part motion.

Rivet Process Overview

The new upset process consists of the following stages;

1. Insertion. Using a high speed skip move which ensures accurate positioning in countersink. A sensor on the front of the upset tool detects when the rivet has bottomed out in the countersink (Figure 3).
2. Servo/Servo move. To ensure that all of the forming load is imparted into the rivet (and not into the surrounding panel surface) the servo driven pressure foot is lifted off the surface of the wing. Simultaneously the servo driven upset tool drives forward to maintain contact with the head of the rivet and ensures no part motion during this step (Figure 4).
3. Rivet forming. Forming is broken down into 4 stages. This is done so that the ramp rate can be varied at each of the 4 forming stages (elastic, plastic stage 1, plastic stage 2, final plastic) (Figure 5).
4. Dwell. The target forming load is maintained for a period of time defined as the dwell.
5. Ramp down. Load is ramped down to a zero load level.

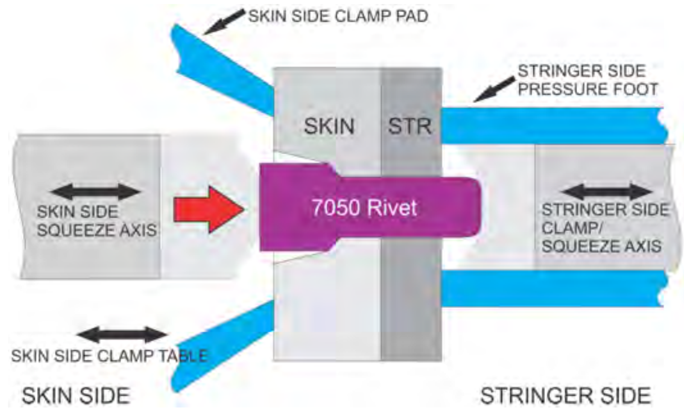

Figure 3. Rivet insertion and seating in the countersink.

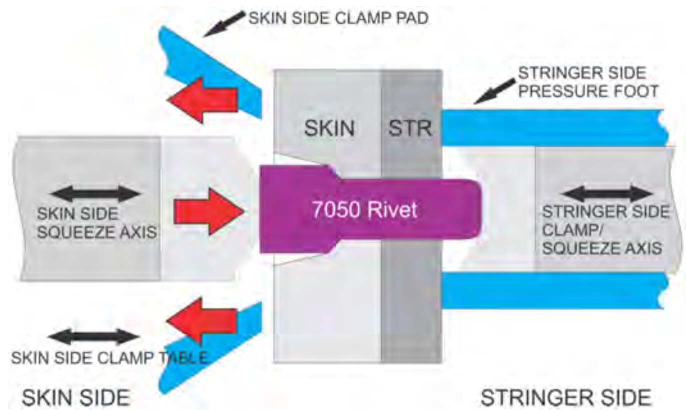

Figure 4. During the Servo/Servo move, the head is pinned into the countersink by the squeeze axis.

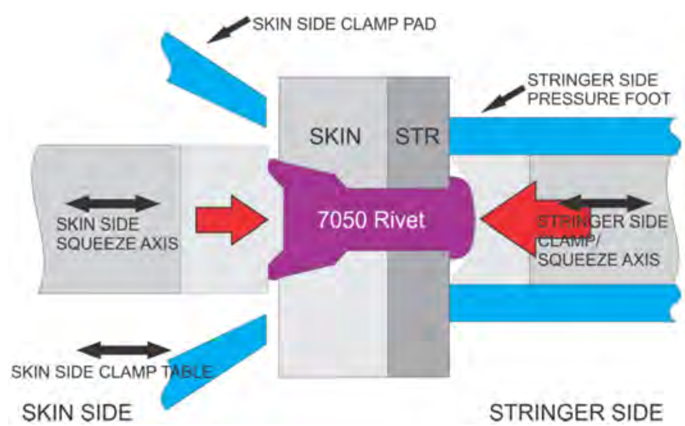

Figure 5. Upset occurs from the stringer side, as the skin side moves to maintain part position.

Figure 6 shows the key characteristics of a traditional, previously-established rivet upset profile. The basic process parameters are forming rate, target upset force, dwell and ramp down rate.

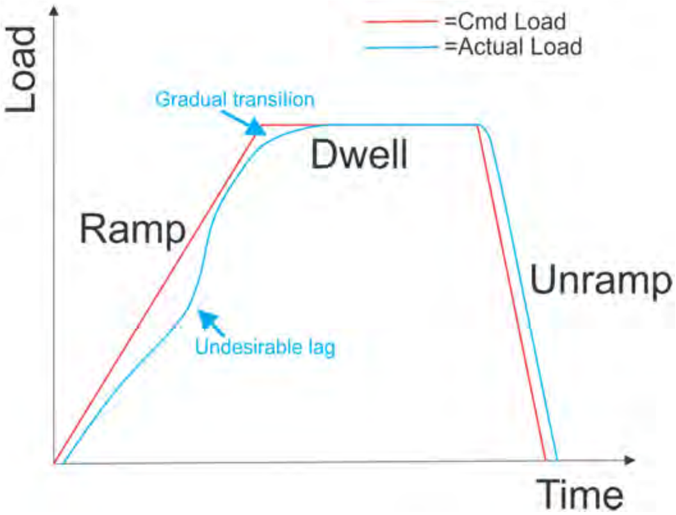

Figure 6. 'Classic' rivet upset profile.

Figure 7 shows the characteristics of the newly developed upset process.

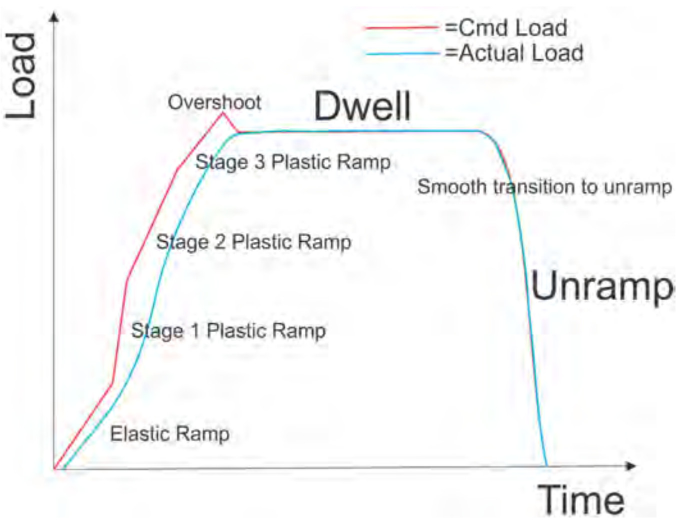

Figure 7. Improved rivet upset profile.

The following features were developed to improve the performance of the rivet forming process;

1. **Variable upset ramp rate.** The rate at which the rivet forms at different stages of the upset process can be specified independently. Varying the rate at different stages of forming affects the interference distribution along the length of the rivet. Figure 7 shows that the actual load response can be improved by manipulating different sections of the commanded load profile. Note the reduction in the undesirable lag seen in figure 6.
2. **Optional overshoot amount.** The commanded load profile can include a deliberate overshoot. It was found that by engineering a deliberate overshoot to the profile, the sharpness of the transition to the target load could be improved. Note that in figure 7 the transition is far less gradual, i.e. the rate of change of load (dF/dt) is maintained at a more constant value up to the target load level.
3. **Accelerated ramp down in load.** To reduce the amount of mechanical shock when ramp down starts, and to allow to overall ramp down rate to be increased, the ramp down is accelerated as opposed to being applied linearly.

Forming Process Software Control Loop

This paper describes a forming process that uses servo actuation from both sides of the fastener. The stringer side of the fastener upset controls the application of force as described in the previous section.

The skin side of the fastener upset controls the motion of the forming rivet and aircraft part as the fastener is upset. The whole forming process typically takes 200ms - 400ms to complete, and during this time the skin side forming axis must move to ensure that there is close to zero net part motion. This is achieved by using a positional command based on the expected amount of motion it would take to form the head of the rivet, and a separate active positional command that is adjusted dynamically during the upset process. This 'active' part of the motion uses a panel motion sensor built into the skin side pressure foot that measures motion of the panel and is accurate to 0.0001″.

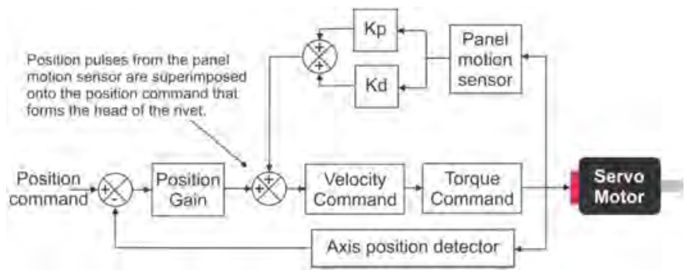

Figure 8. Skin side forming axis process control loop.

Figure 8 shows the control loop design for the skin side forming axis. A proportional/derivative loop was used to handle the feedback from the panel motion sensor at an interval of 1ms. The output from this loop is added directly to the output of the CNC's own position loop every 8ms. This combined position command is then used to drive the skin side upset axis to maintain near zero part motion throughout the rivet forming process.

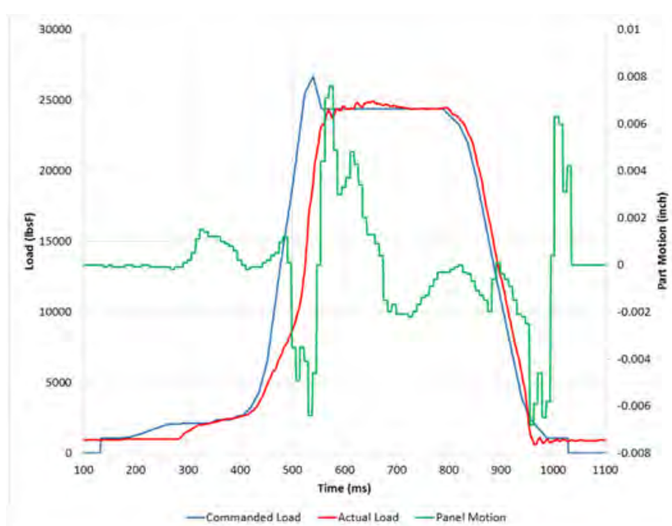

Figure 9. Plot of panel motion during upset.

Panel motion was measured and recorded for every fastener upset during process development (and continues now the system is in production). Figure 9 shows an actual forming plot showing load command, measured load and measured part motion (less than +/− 0.008″ in this case).

This design of high speed control loop allowed for upset rates of up to 200,000lbs per second whilst maintaining panel position to within +/− 0.010″.

Challenges of High Speed Upset

Vibration Suppression

High speed rivet upset using servo driven axes has the benefit of high acceleration performance of the axis (compared to typically slower performance of hydraulic systems).

However this benefit has the secondary effect of introducing mechanical shock into the machine and aircraft part, resulting in vibration. An example of where this was encountered and overcome was the transition point from the dwell to the ramp down. It was observed that on certain larger sizes of rivet there was a large variability in the interference at D4 (close to the exit of the hole).

This variability was investigated, and linked to a vibration in the system initiated by the mechanical shock which occurred when the ramp down in load started at the end of the dwell.

Figures 10 and 11 show the vibration and resulting 50% reduction in vibration when a smoother transition from dwell to ramp down was introduced. Improvements of this nature were made in several parts of the upset profile and contributed to an overall improvement in stability which led to a reduction in the standard deviation of rivet interference results.

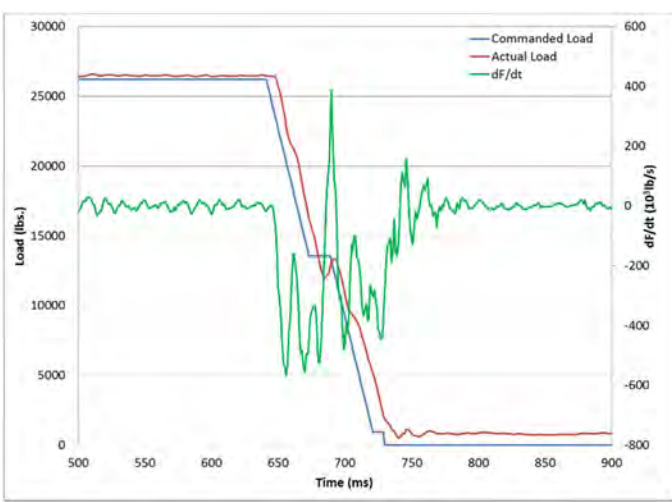

Figure 10. Vibration in measured load during sharp transition from dwell to ramp down.

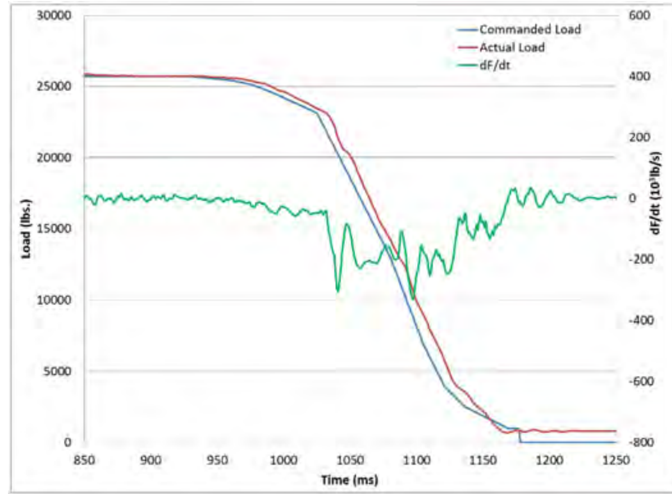

Figure 11. Reduced vibration in measured load during smoother transition from dwell to ramp down.

Strategies to Improve Transition from Ramp to Dwell

It was discovered during the course of development that the transition from ramp to dwell can have a significant impact on rivet interference patterns. A sharper corner (i.e. higher dF/dt is maintained up to the dwell) has the effect of lowering interference at the countersink and D4 (exit of the hole) and increasing interference at D2 (skin/stringer mating point). A description of the key measurement locations of formed rivets (D1, D2 etc.) may be found in the appendix.

In order to produce the best performance at the transition from ramp to dwell, it was discovered that adding a deliberate overshoot resulted in the most favorable shape for the actual load profile for most rivet diameters and grip lengths.

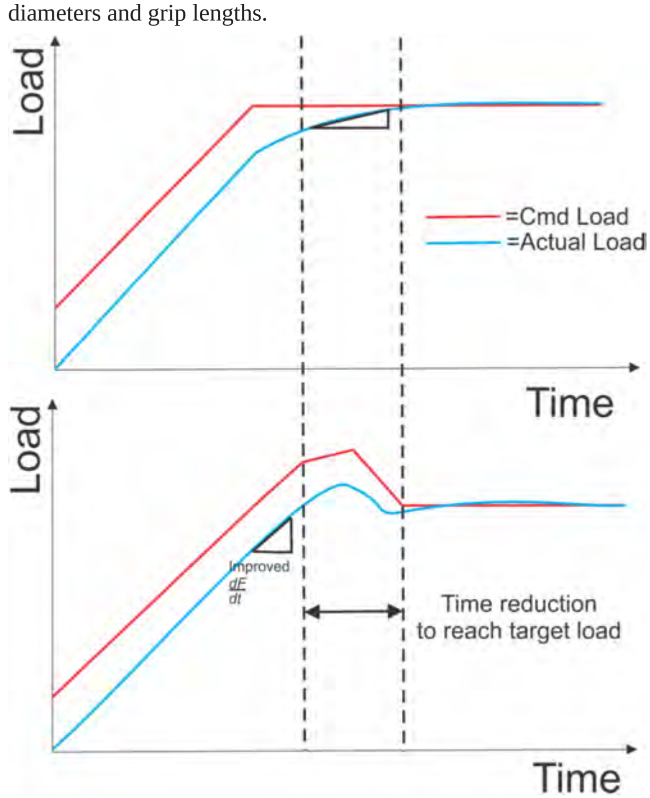

Figure 12. Showing a zoomed in view of the upset load profile at the transition from ramp to dwell. The first image shows a standard transition, while the second shows the improved performance by adding artificial overshoot.

The performance improvement achieved by adding an artificial overshoot was superior to that achieved by increasing the force control proportional gain, since the latter led to stability degradation while the former did not. Figure 12 shows the improved performance at the transition point. Note, not only the higher dF/dt at the transition, but also the reduction in time to reach the target load.

Effects of Protrusion

Aerospace rivet grip lengths are standardized to 1/16th″ increments. Therefore any given grip length has an acceptable stack range of 0.0625″. Different amounts of protrusion (the amount of rivet protruding from the hole after forming) were found to produce different upset profiles and this had an adverse effect on the consistency of both interference and panel motion across the stack range of any given grip length of rivet.

It was noted that by varying the rate of application of load into the rivet (the ramp rate) the forming profile could be manipulated at the minimum and maximum stack to be similar to the profile seen at the mid stack. A linear relationship between adjusted ramp rate (R) and stack (S) was devised. Most grip lengths required a ramp rate adjustment (α), with the minimum stack ramp rate adjusted to be slower than the nominal ramp rate (R_{nom}) used for the mid stack (S_{mid}), and the maximum stack (S_{max}) ramp rate adjusted to be faster than the mid stack nominal ramp rate:

$$R = R_{nom}\left[1 + \frac{\alpha(S - S_{mid})}{(S_{max} - S_{mid})}\right]$$

This ramp rate adjustment factor is built into the machine software and is applied automatically based on the selected rivet grip length, the stack range for that grip length, the measured stack and the baseline nominal ramp rate (i.e. the ramp rate at mid stack).

Independent Profile Recipes Per Grip Length

In order to account for differences in the interference requirement of specific rivets it was decided that a very granular level of control would be provided on a per grip length basis. A list of key forming parameters (otherwise known as an upset recipe) was developed, and a table of these parameters provided that could be referenced for a given grip length of rivet. For rivets with similar forming characteristics, the same upset recipe number could be specified.

A sample of recipe parameters can be found in table 1.

Table 1. Shows a sample of rivet upset recipe parameters and units. See figure 7 for upset stage number explanations.

Target Force (How much upset force is imparted)	Lbsf
Rate (Baseline overall rate)	Lbsf/sec
Dwell (How long to pause after forming before retracting)	ms
Driver Servo Target Position (Rivet Head Height)	Inches
Overshoot Enabled (Enable deliberate overshoot or not)	No Units
Stage 1 Ramp Rate Multiplier	No Units
Driver Servo Extra Unwind	Inches

This granularity of control allowed for the idiosyncratic behavior of certain rivets to be overcome by creating a unique upset recipe for that particular fastener.

SUMMARY/CONCLUSIONS

A new ballscrew-based process for index head rivets has been introduced and has been shown to perform well at high forming rates. This new process has been an integral component of a one-up wing panel assembly process by allowing aircraft components to be rigidly indexed. Panel motion is kept at near zero levels by accurate insertion into the countersink, together with a novel ‘servo/servo’ move to accurately constrain the head of the rivet into the countersink. During forming a closed loop system allows the position of the aircraft panel be held to within +/− 0.010 during upset at rates of up to 200,000lbs/sec up to an upset force of 40,000lbs.

During the development of the new riveting process it became clear that certain specific grip lengths (and skin/stringer combinations) presented additional challenges in meeting interference and fatigue requirements. It has been shown that by implementing greater flexibility in the fastener forming process, specifically allowing the shape of the upset profile to be manipulated, improved interference results can be achieved. Adding an artificial overshoot to the commanded load profile, and the resulting changes to the actual load profile at the transition from ramp to dwell has been shown to improve the interference characteristics of the formed rivet, specifically a reduction in interference at D4 and an increase at D2.

High speed servo driven rivet upset has been shown to perform well at high upset rates by implementing measures to overcome mechanical shock. The specific example of vibration during unwind was explored in this paper, and enhancements to the profile shape were shown to reduce vibration by 50% and reduce process variation. It was found that over the stack range of a particular grip length the shape of the rivet upset profile (and resulting interference of the riveted joint) could vary significantly, in some cases producing undesirable results. Varying the ramp rate as a function of rivet protrusion has been shown to produce more stable results over the entire stack range of a given grip length.

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DEFINITIONS/ABBREVIATIONS

dF/dt - Rate of change of force with respect to time.

CNC - Computer numerical control.

K_p - Proportional Gain

K_d - Derivative Gain

CSK - Countersink

APPENDIX

RIVET INTERFERENCE MEASUREMENT LOCATIONS.