Development and Post-testing Anomalies of the Parker Solar Probe Clamshells

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Abstract

The Johns Hopkins University Applied Physics Laboratory built and flew a novel deployable antenna containment mechanism specifically for use on Parker Solar Probe. These mechanisms came to be known as "the clamshells"; a moniker earned for a deployment that was reminiscent to the movement of their ocean-bound namesake. This document describes the fundamental design and development efforts associated with these mechanisms. Furthermore, it will delve into to the subsequent investigation of the deployment anomaly that that occurred during protoflight testing and resulted from dimensionally non-compliant parts and effects of titanium-to-titanium galling.

Introduction

The NASA Parker Solar Probe (PSP) spacecraft, built by the Johns Hopkins University Applied Physics Laboratory (JHU/APL), was launched from Cape Canaveral, FL on August 12, 2018. The spacecraft, shown partially in Figure 1, will provide new data on solar activity and make critical contributions to our ability to forecast major space weather events that impact life on Earth[1].

During the development of PSP, APL conceived, fabricated, tested and integrated a unique, partially deployable antenna containment system for launch and testing environments. These mechanisms were successfully deployed two days after the launch of Parker Solar Probe. Formally referred as the Antenna Retention System (ARS), this late-stage development effort served the purpose of attenuating the anticipated excursions of the ~2100 mm (~82 in) niobium V1, V2, V3 and V4 FIELDS instrument antennas (provided by the Space Sciences Laboratory at the University of California, Berkeley) during spacecraft (SC) testing and launch. A result of the flexible nature of the antennas, their stowed mounting location, and the fact they spanned multiple SC interfaces, containment was necessary to prevent damage to other SC components. The ARS system, as depicted in Figure 1, is comprised of a one-time deployable, SC structure-mounted clamshell mechanism, and a series of static fork-shaped snubbers mounted to the thermal radiators directly adjacent to the instrument hinge. The deployment of the clamshell mechanism is completely independent of the FIELDS deployment hinge; the former is deployed first, enabling the latter to individually deploy each antenna from the stowed launch position to the final, radially extended configuration beyond the umbra of the Thermal Protection System. Each of the four FIELDS antennas have a corresponding clamshell mechanism, and a set of carefully aligned forks adjusted to the natural shape of the stowed antenna. The clamshells at the FIELDS V1 and V2 locations shared similar mounting bracket geometry, V3 and V4 mounting brackets were completely unique to the others (Figure 2). Though the mounting brackets varied, the clamshell mechanism at each location were identical.

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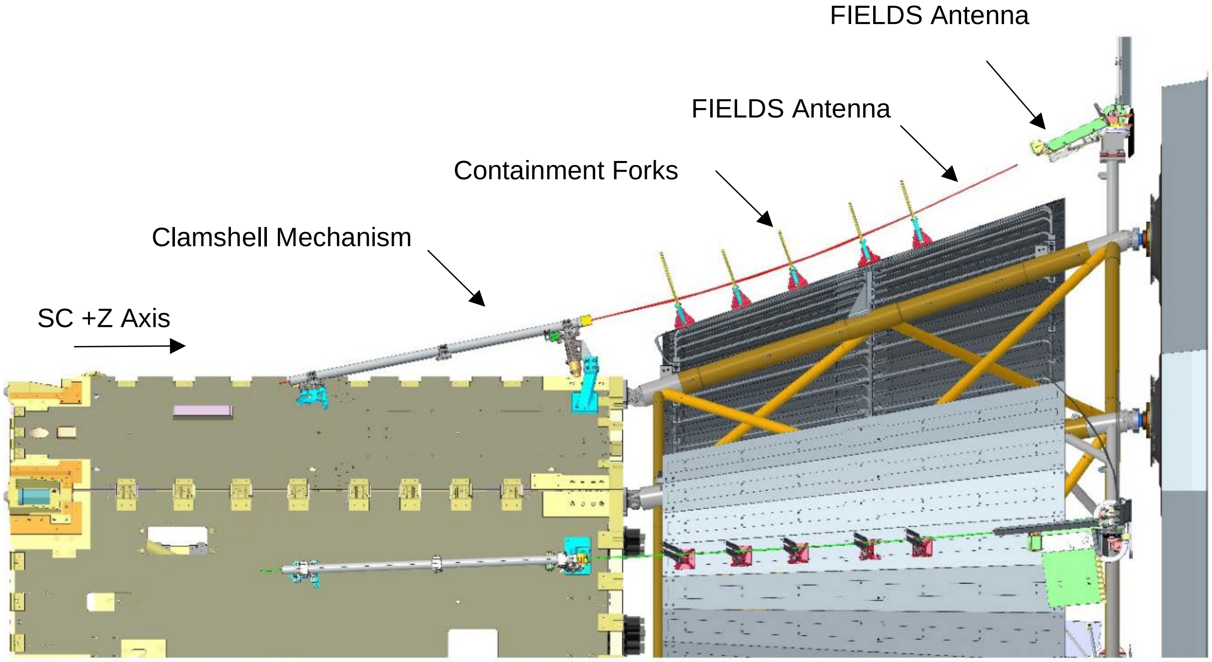

Figure 1: PSP Side view: The primary components of the Antenna Retention System (ARS) and FIELDS instrument on Parker Solar Probe

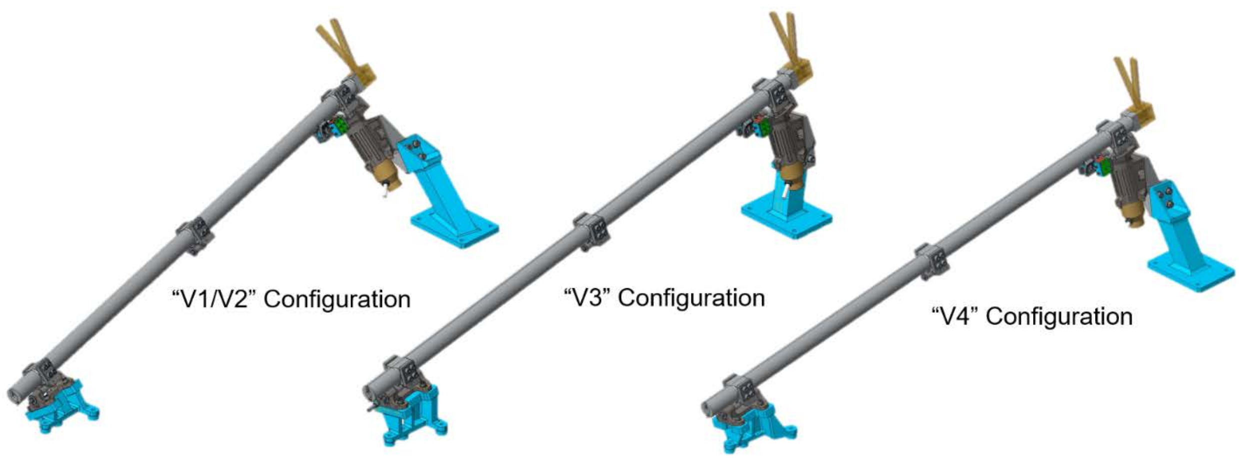

Figure 2: The three variations of the clamshell mechanism mounts for 4 different mounting locations

Clamshell Mechanism Design

The PSP clamshell mechanism is comprised of two, half-circular machined aluminum halves, one deployable or active hinge, two follower hinges, redundant deployment telltale switches, and plastic antenna guides that are mounted to the top end of the clamshell. The clamshell halves are 762-mm (30-in) long, have a 22-mm (.875-in) external diameter, and are fabricated from 6061 aluminum, with aggressive mass-reduction features on the inside. The clamshell mounts to the PSP SC bus via features on the top and bottom hinges, on brackets that position each clamshell on a natural tangent of each stowed antenna. These brackets were designed with multiple bolted interfaces to provide multiple degrees of in-plane angular and translational adjustability to ensure proper in-situ alignment with each stowed antenna.

Figure 3: Top view: The clamshell mechanism that corresponds to the V1 FIELDS antenna position.

When deployed, the clamshells hinge open along the length of the tube created by the halves. They do not open much; only 15 degrees per half (Figure 4), but this is more than sufficient to release the 3.2-mm (.125-in) diameter antenna. They are not designed to physically clamp or restrain the antenna, but only to loosely contain it. The 6.4-mm (.25-in) clamshell ID enables to the antenna to rattle slightly and freely translate axially, as not to impart any additional loads into the FIELDS instrument from the SC deflections that occur during SC vibration events. The closed side of one clamshell half features an “anti-trapping” tab along its length, to prevent the antenna from getting hung up or caught in the gap formed when the mechanism is deployed. Similarly, the yellow Ultem® blocks on the end of each clamshell half ease the transition of the antenna into the end of the tube; a location determined to have the highest dynamic contact. Extensive material testing was performed to ensure Ultem® compatibility with niobium antennas.

Figure 4: Top view: The clamshell mechanism depicted in the closed (left) and open (right) condition.

The heart of the mechanism, the active hinge, utilizes a TiNi Aerospace P10 Pinpuller to provide the motive force to deploy the greater mechanism. A TiNi P10 pinpuller is designed to retract 9.5 mm (.375 in) with 44 N (10 lbf) of pulling force[2]. Due to the shear load limitations of the pinpuller pin as specified by TiNi, it was necessary to isolate the vibration loads imparted by the mass of the clamshell from the pinpuller pin. This isolation is performed by a titanium slider cup, which is fastened to the end of the pinpuller via a loose spherical interface and engages two titanium legs built to each clamshell hinge half. When the pinpuller is actuated, the sliding cup translates along the axis of the pin, disengaging the clamshell legs, and enabling each spring-loaded clamshell half to pivot open (see Figure 5). The spherical interface between the

Pinpuller pin and the cup prevents binding of the sliding cup in the housing by eliminating all potential over-constraining degrees of freedom. The intentional loose fit of the spherical interface ensures that no external moments or side loads can be imparted onto the pinpuller pin due to assembly tolerances or launch shifts. Only the retraction force can be imparted into the cup.

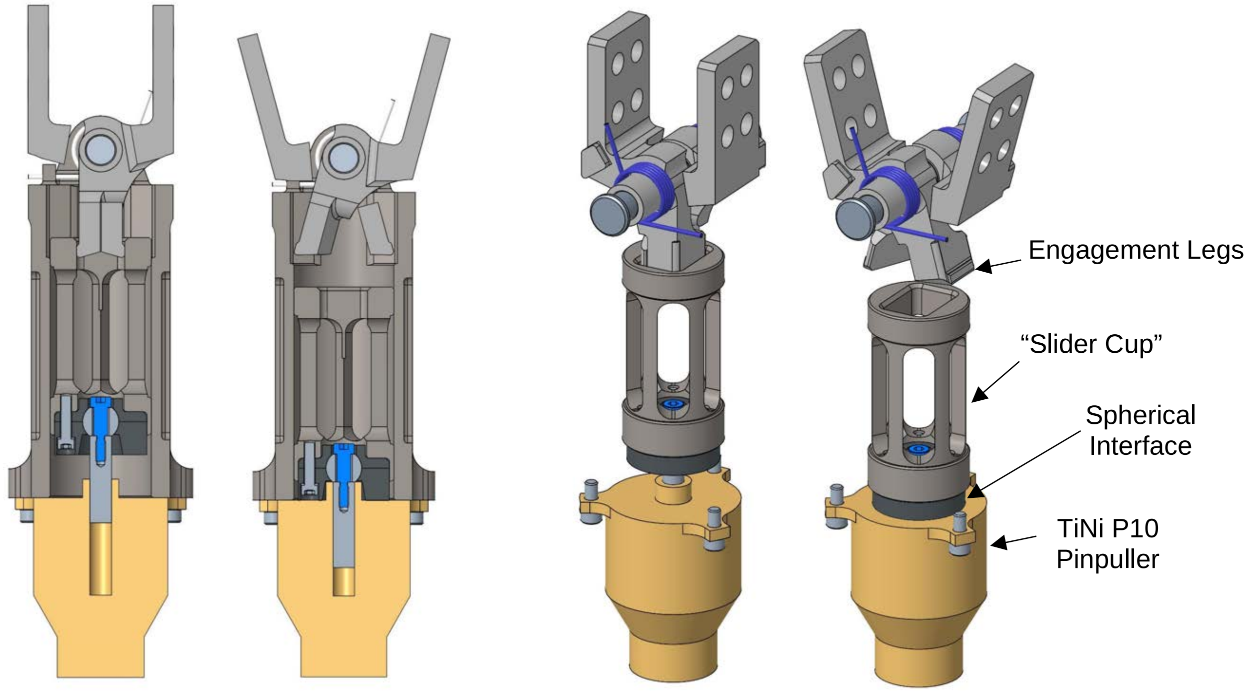

Figure 5: The details of the active clamshell hinge, in stowed and deployed positions. Left: Cross-section, Right: Housing not shown

The other two hinges are spring-loaded follower hinges that simply provide additional opening torque via torsion springs at each location. These hinges feature no release mechanism or lock, and the mass of the center hinge is supported entirely by the clamshell halves. The bottom hinge is designed to accommodate ±3.2 mm (.125 in) of change in the axial length of the clamshells (Figure 6), and this eliminates the potential for the mechanism to bind from temperature-induced dimensional changes (CTE). Furthermore, the bottom shaft was cut with a profile of spherical undercuts, to further minimize the potential for binding, and provide additional angular adjustment during SC integration.

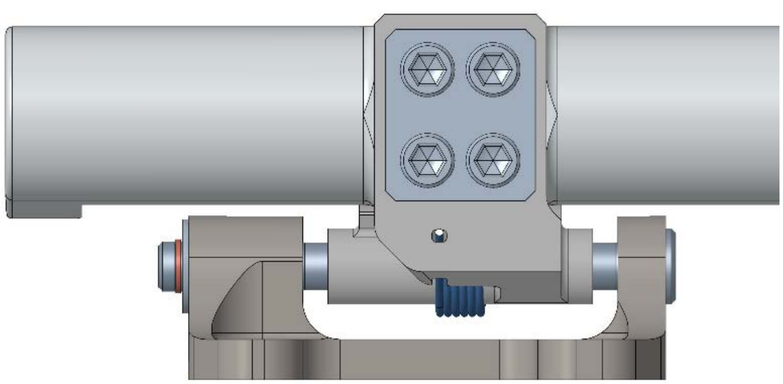

Figure 6: A side view of the bottom hinge illustrates the bottom mounting bracket and the gaps designed to accommodate CTE effects of the aluminum clamshells

Also attached to the active hinge bracket are four Honeywell 9HM1 micro switches to provide redundant deployment telltale signals of each clamshell half. Resistors of different values were placed in-line in the harness, as to indicate “left-open”, “right-open” and “fully-open” states. A small aluminum lever arm attached directly to the clamshell engaged the switches directly when stowed (Figure 7) and disengaged only when the clamshell reached the fully open, 15-degree state. These switches functioned perfectly upon the actual deployment in space but proved to be very difficult to set and tune on the ground. The #2 attachment screws needed to be torqued enough to prevent shifting of the switch, but not so much to crush the thin exterior case. The risk of a false telltale reading was also partially mitigated by analyzing the SC IMU data to show the shock of each at deployment.

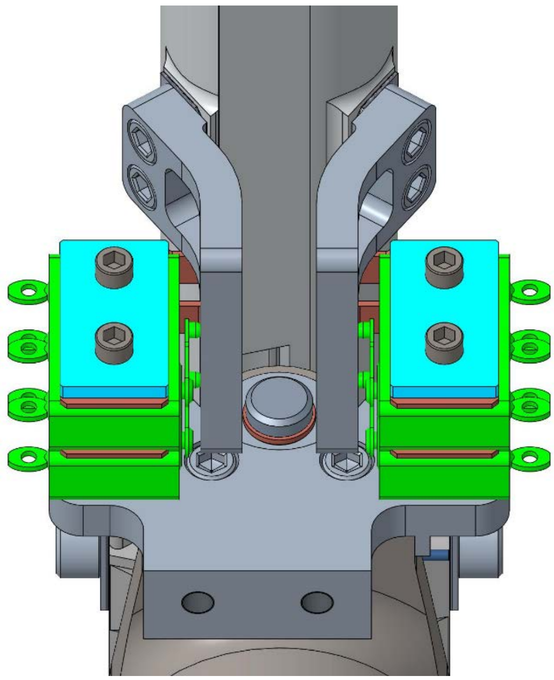

Figure 7: A bottom isometric view of the redundant telltale switches

Materials and Coatings

The mounting brackets and clamshell halves are fabricated from aluminum, and are iridite coated and electroless nickel plated, respectively. All of the mechanism parts are 6Al-4V titanium, including the active hinge housing, the sliding cup, the hinge halves and shafts. This fact becomes an important detail in the anomaly investigation to be detailed later. The decision to uniformly fabricate all mechanism parts from titanium was made to eliminate the effects of CTE mismatch within the tightly-fitting, high-precision mechanism components, and in some cases, for strength considerations. The two halves of the titanium spherical interface screwed onto the pinpuller are unfilled PEEK, the springs are Elgiloy®, and all the fasteners are stainless steel.

All titanium mechanism components are titanium anodized with a type 2 Tiodize® process, with local application of Dicronite® (tungsten disulfide) dry film lubricant on all moving or sliding surfaces. No additional lubrication was used in the assembly, except on the fasteners.

Development Effort

As a result of the late schedule addition of the Antenna Retention System, the clamshell mechanism was developed on a very aggressive timeline. Two engineering model (EM) versions of the clamshell mechanism were built and tested before the flight units were fabricated. The first EM provided a successful proof of concept of the mechanism, and the environmental testing scheme. The second EM implemented most of the flight-like mass reduction efforts and added the telltale switch assembly. The differences between the second EM and the flight implementation were intentionally very minor, including maintaining EM2-to-flight continuity with the fabrication shops selected for each part.

Each iteration of the design was fully vibration (Figure 8) and thermal vacuum (TVAC) tested, and dozens of ambient temperature, post-vibration and hot/cold deployments (Figure 9) were executed. Additionally, ARS system-level containment tests were conducted at three points during the PSP development effort: during the SC modal test, the full SC vibration test, and a specially built SC “stiffness simulator”, as shown in Figure 10. This simulator provided a test bed to perform ARS-level tests at higher vibration levels, while eliminating the risk to the actual SC bus. In each case, surrogate FIELDS antennas were captured in EM clamshells and forks. Efficacy of the retention system was determined through high-speed video and measurements from the video of the antenna maximum excursions as observed during the modal test, and the SC stiffness simulator vibration tests. The flight clamshells were qualified separately and added to the SC after the complete SC vibration test, but before the complete SC TVAC test.

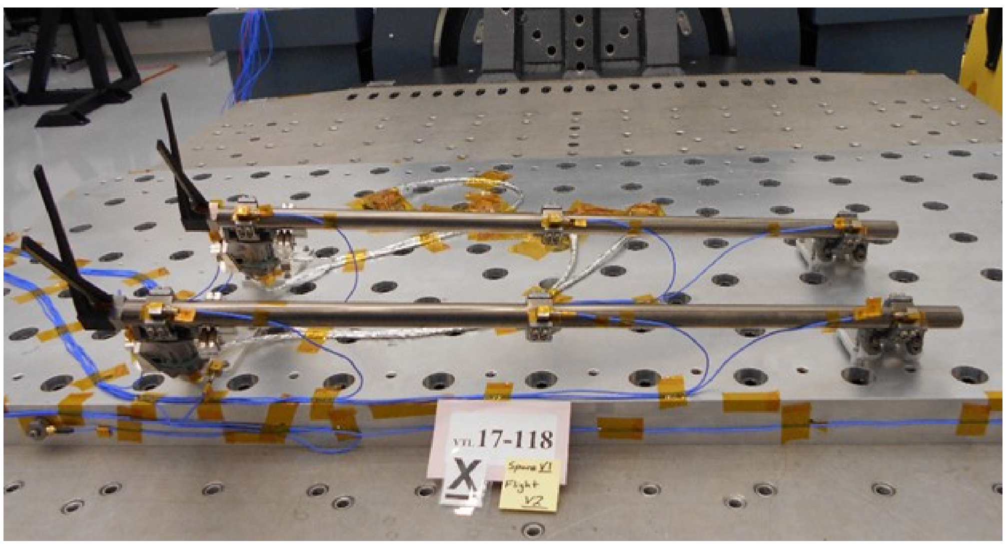

Figure 8: V1 and Spare flight clamshells on a vibration table

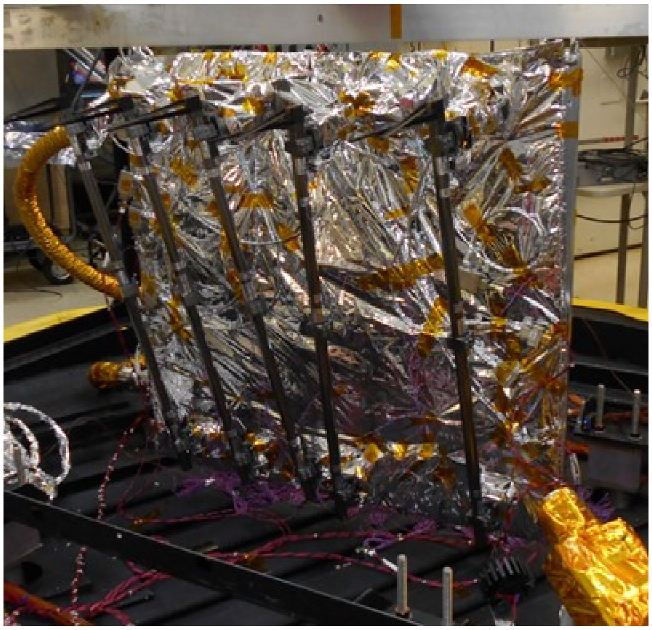

Figure 9: Flight clamshell mechanisms staged for TVAC testing.

With the exception of some erroneous telltale indications observed during the EM2 clamshell development, no anomalies occurred during mechanism-level testing. The telltale design was modified and follow up thermal and vibration testing was conducted to verify the correction. This was considered to be a reasonable step in the development process, and while additional attention was given to the telltale configuration as a result, it was not considered to be a serious anomaly. No deployment failures occurred through EM2 development, and the clamshells enjoyed a perfect record of functionality.

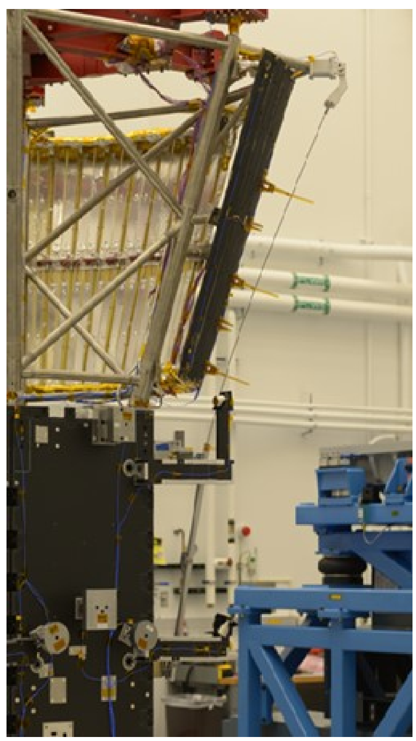

Figure 10: Left: EM Clamshell with preliminary fork configuration.
Right: EM Clamshells on structure "stiffness simulator"

Anomaly Investigation

Despite a successful testing campaign of the first and second EM iterations of the clamshell mechanism, an anomaly of the V3-position flight clamshell occurred immediately following protoflight vibration testing. The unit failed to actuate; the proper voltage was sent to the TiNi Pinpuller, a faint click was heard, but no movement was observed. The electrical ground support equipment (EGSE) was checked, determined to be functional, and voltage was applied to the redundant (backup) circuit of the pinpuller, yielding the same result, but with no additional audible click.

The frozen clamshell was carefully photographed in this state, and a course of action was devised. It was unknown at that time if the failure was contained to only the pinpuller, or if was problem at a higher-level assembly and something in the rest of the mechanism was bound. As the mounting screws were being carefully (no shocks or bumps) removed from the top mount to the titanium hinge housing, the clamshell deployed. From this event, it was theorized that perhaps the distortions in the housing caused by the screws prevented the cup from sliding down a perfectly straight bore. This also immediately indicated that the problem was not isolated to the pinpuller, which was maintaining a constant 44-N (10-lbf) pull force, and that there were external effects acting on the greater mechanism. Despite the deployment, a fish scale was attached to the back of the pinpuller to measure the extraction force necessary to remove the sliding cup and pinpuller assembly (Figure 11). 36 N (8 lbf) was measured; it should have been nearly zero. With the addition of the predicted 18-N (4 lbf) disengagement force necessary to actuate the hinge legs, the 53-N (12-lbf) combined force is outside the operational capabilities of the P10. Along with the extraction of the cup, dark, powder-like FOD was observed to come out as well. This FOD was collected for chemical analysis, and it was determined to be comprised primarily tungsten disulfide powder, with a combination of trace amounts of titanium. This was FOD produced from the mechanism itself, and not from an external source. This was not an anomaly that was caused by mishandling or a dirty environment.

Figure 11: Removal of the sliding cup and pinpuller assembly, immediately after deployment anomaly

An extensive investigation effort was initiated to determine the root cause of the V3 clamshell anomaly, focusing on the following aspects: the design of the mechanism, the manufacturing process, the testing environment, and the selected materials. A fishbone diagram (Figure 12) was created, and each potential contributor was subsequently investigated. The theory that the housing distorted enough to bind the cup was quickly discounted through additional FEA analysis.

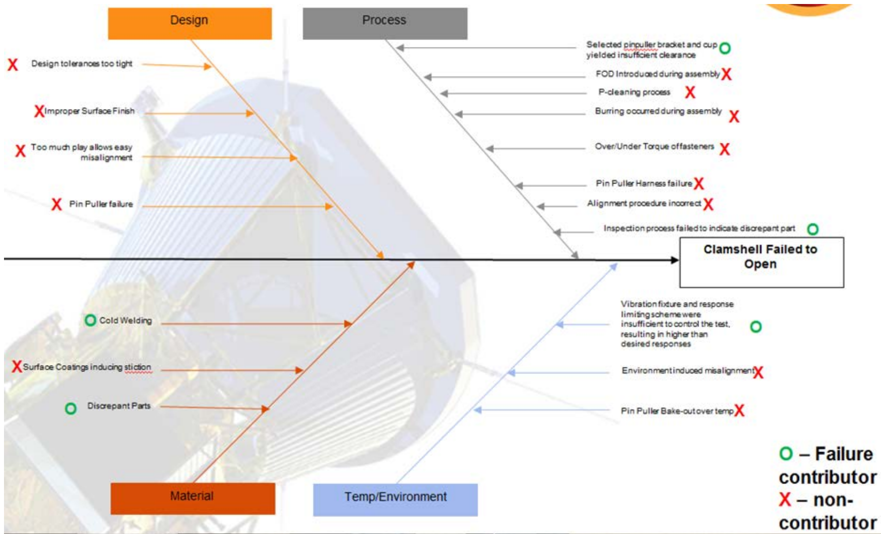

Figure 12: Completed clamshell Failure Review Board investigation fishbone diagram

Upon removal from the housing, the pinpuller was evaluated electrically and mechanically for functionality. It was quickly determined that it was destroyed; it physically could be reset and maintained a constant spring force, but it could not be actuated via either circuit. Though initially suspect, the damaged Pinpuller was determined not the root cause of the failure, but a side effect that resulted. TiNi Pinpullers are designed to automatically disconnect and shut off the flow of power upon actuation. If the Pinpuller were physically prevented from actuation, as was the case in this situation, the electrical contacts will remain closed, overheating the actuation element. The nature of the EGSE being used to conduct this deployment (power supply with push button) resulted in power being applied to the devices applied for much longer period of time than designed. Typical Pinpuller actuation times are 30 to 80 msec (dependent on device temperature)[2]; so an uncontrolled button press of approximately 1 second is an order of magnitude too long, resulting in irreversible damage to the nickel titanium shape memory actuation wire. One of the lessons learned, and immediate changes made as a result of this anomaly, was to implement EGSE and on-board SC commands that provide a pre-determined pulse of current, instead of a simple button press. This has the effect of protecting the Pinpuller from electrical damage in the case of a frozen mechanism, both during testing, and in space.

It was apparent however, during close inspection of the sliding cup that was forcefully extracted from the housing that there were very small (0.1 mm, 0.0039 in) areas of damage at the bottom of the cup. These three areas were spaced about 120 degrees apart, radially, on the circumference of the sliding cup. There were corresponding areas of similar damage on the housing as well. Instead of material buildups like on the cup, the housing damage was manifested as shallow pits. It was obvious that there was a transfer of material, and that these build-up locations (Figure 13) on the cup were substantial enough to close the gap between the sliding cup and the housing; effectively seizing the cup in place. These areas were photographed and documented with the aid of a microscope.

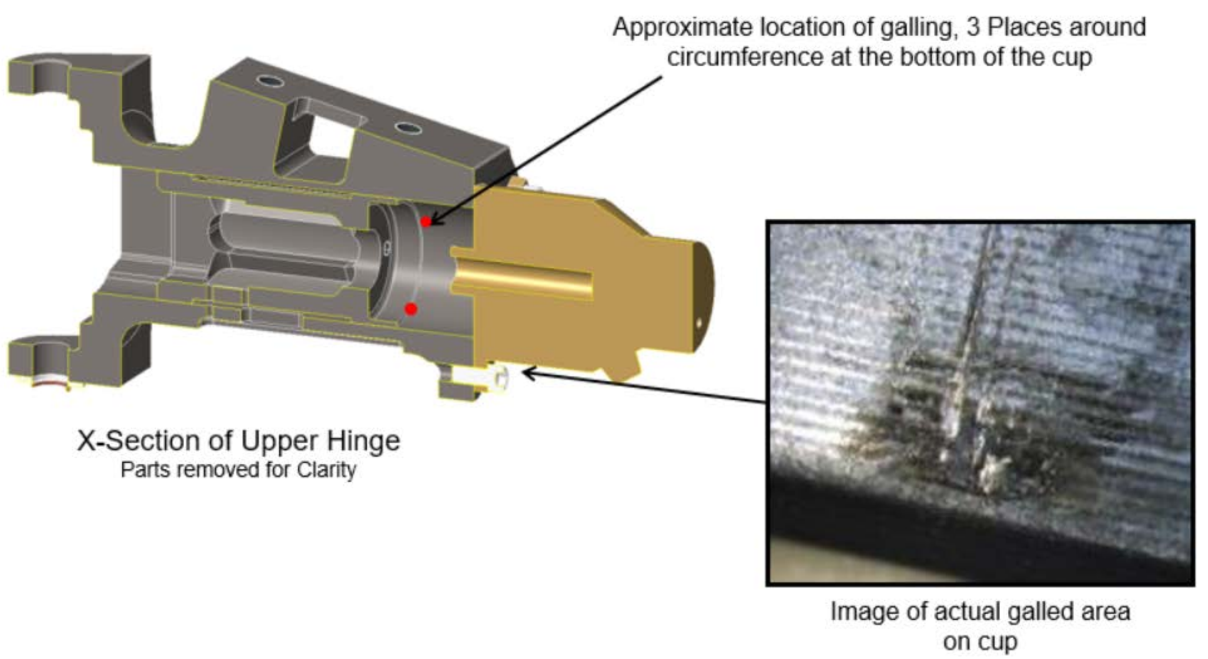

Figure 13: Locations and micrograph of damaged area on the circumference of the sliding cup

Dimensional Analysis

A detailed investigation of the dimensional clearance between the cup and the housing began, to determine what the realized clearances between the two parts were, and if they were designed to be too tight. All previous clamshell mechanisms (EM1, EM2, and Flight) were disassembled and each housing and cup part measured. Up to this point, each iteration of both the housing ID and the sliding cup OD were only spot checked; only one measurement of each were taken of one part in the lot. In addition to the full post-inspection, it was determined that the profile, or effective shape of the parts should be measured and ascertained as well. This was accomplished by taking multiple diameter measurements of each part, in the critical areas of part interaction. As depicted in Figure 15 these diameter measurements were made in 1.27mm (0.050 in) step increments along the length of each part.

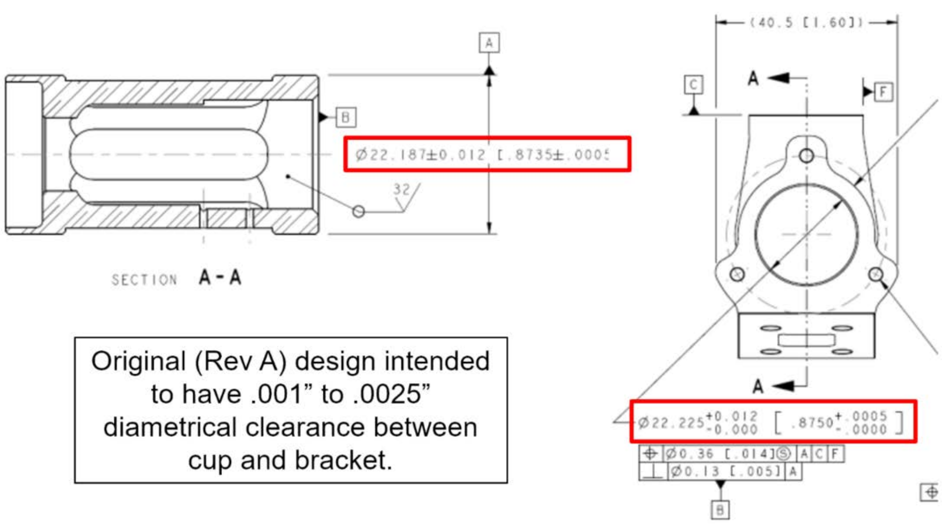

Figure 14: Snippets of original flight drawings of critical diameter dimensions and tolerances

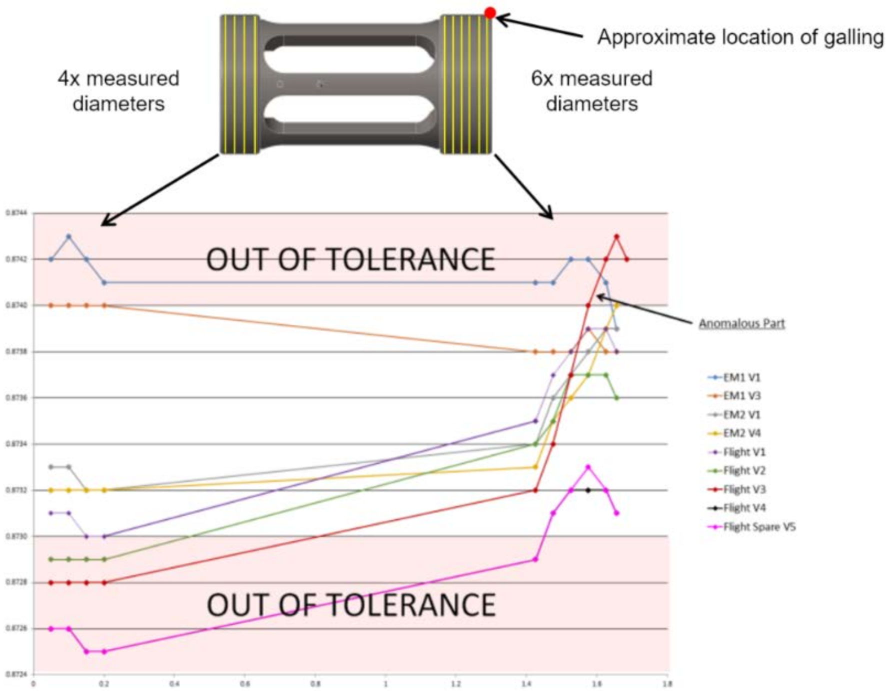

Figure 15: Detailed measurements and shape of all sliding cups fabricated up to the time of the anomaly

This inspection process was illuminating, as it became immediately clear that the specific sliding cup that seized was out of family from all of the other sliding cup parts that were fabricated during the entire mechanism development effort. In addition to the effects of a larger outside diameter sliding cup, which effectively reduced the diametrical gap between the parts to half (.022 mm, .0009 in), (Figure 16) from the average nominal (.045 mm, .0018 in), but the back half of the sliding cup was tapered over .0254 mm, (.001 in) diametrically over the distance of approximately 8 mm (.32 in). The spots where the damage occurred corresponded exactly where the diameter was the largest. The resulting tapered-shape adds credence to the theory that the affected sliding cup was contacting with the housing on a line profile only, as opposed to the distributed as-designed surface contact of a correctly fabricated cylinder. A line contact would effectively magnify the contact stresses to the reduced areas of contact during the vibration testing that was performed immediately prior.

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Figure 16: Relationship of all housing/slider fits EM1 through flight (dimensions in inches)

Material Discussion

With the dimensional issues with the anomalous part in revealed, the investigative team focused on the selected materials as a contributor to the root cause of the problem. A mentioned earlier, both the sliding cup and the housing were coated and dry film lubricated 6Al-4V titanium; a decision made to eliminate any potential CTE effects within the mechanism. The tendency for bare titanium to wear and gall to itself is well documented, particularly for space applications, where solid-phase welding can occur at areas of high friction and elevated pressure despite temperatures well below the melting point[2]. The effects of this material phenomenon were considered to be mitigated in this mechanism through proper selection of surface coatings and lubrication; a position supported by the lack of any other example of titanium-titanium galling or during the clamshell development. Despite the presence of those coatings, it is theorized that the increased contact pressure that resulted from the tapered-cup line contacts, was enough to transfer titanium material from the housing to the sliding cup and lightly cold-weld the two together. This deposition filled the reduced gap between the parts and increased the sliding force beyond the capabilities of the 44-N (10-lbf) pinpuller. The combined effects of a singular out of tolerance part and localized titanium-titanium galling was determined to the root cause of this anomaly. These effects were further exacerbated by control issues observed during testing; some clamshell configurations experienced higher dynamic loads than others, but that is a topic worthy of a different paper.

Corrective Action

Several Failure Review Boards were held as a result of this incident, with reviewers invited from outside organizations. With the root cause identified, a mitigation plan was developed, and unanimously supported by the board. Ultimately, a complete set of new active hinge halves, housings and sliding cups and were re-fabricated as a result of this anomaly. In an additional risk mitigation step, an entire new set of TiNi P10 pinpullers were procured as well, because the previous set had uncontrolled-length current pulses applied to them from the EGSE. Each mechanism part was fully inspected to the same level of scrutiny as the parts measured during the investigation, to ensure a minimal amount of part taper and shape. The inspection data was then used to match the cups and the housings to each other to guarantee a minimum .055-mm (.0022-in) diametrical gap in each assembly. Strategic material changes were considered, like a leaded bronze sleeve between the cup and the housing, but the review board deemed such a drastic change to be too risky. There was no available volume for the additional thickness of a sleeve. Despite being considered a risk, the original coated and lubricated titanium parts remained in the design.

The clamshells were already slated to be integrated late in the SC I&T schedule, so the delays associated with this investigation and corrective action necessitated a considerable amount of re-planning and schedule modification. Though EM2 clamshells were present in two locations on the flight structure during SC vibration testing, the new flight units had to be qualified individually, separate from the SC. The final integration of the clamshells occurred in early 2018, weeks before the full SC TVAC test. This was a hard deadline; four deployed clamshells had to be present on the SC to gather relevant thermal balance data. Final alignments of the complete ARS system were performed months later, in May 2018.

Conclusion and Lessons Learned

There is an adage that states generally, "*All testing failures are good failures",* and this anomaly is a perfect example of the truth in that statement. Though severity of this issue can be debated, the marginal nature of the failure (the pinpuller almost had enough force to overcome the cold-welds) presents a potential scenario that had this failure not occurred when it did, it could have resulted in a much larger problem later in the mission. Had the V3 clamshell deployed as expected, the damage may not have been detected until it was too late. That damage could have further compounded during SC vibration tests and launch, resulting in a worst-case scenario where the mechanism didn't deploy when it needed to in space. In addition to a partial loss of Level-1 mission requirements on a flagship NASA mission, the failure investigation would have been impossible to complete with certainty. A lack of comprehensive inspection data, and the parts impossible to recover, only postulations could be made about a true final root cause. Ultimately, this anomaly and subsequent investigation resulted in a more robust, and reliable mechanism that enabled mission requirements to be met.

Primary Lessons Learned:

- Avoid dynamic titanium on titanium interfaces, and do not rely on surface coatings and lubrication to fully mitigate galling and cold welding effects.

- Fully inspect all size and form critical mechanism components.

- Anomalies can beget additional anomalies, which can become red herrings and distractions in an investigation. This was the case with the EGSE-damaged pinpuller.

- Take steps, however conservative, with GSE to protect the hardware. Both MGSE and EGSE used during this development exacerbated the anomalous conditions.

Acknowledgements

The fantastically supportive and professional Parker Solar Probe development team at the Johns Hopkins University Applied Physics Lab.

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