SUBSTITUTION OF SPRING CLAMPS FOR BOLTS ON SRF FLANGES TO MINIMIZE PARTICLE GENERATION*

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Abstract

Hyperboloid LLC developed and successfully tested a System of High Force Spring Clamps to substitute, one for one, for bolts on the flanges of SRF Cavities. The Clamps are like exceptionally forceful binder clips. The System, that includes the Hydraulic Openers that apply the clamps, minimizes generation of particulates when sealing cavity flanges. Hyperboloid LLC used ANSYS to design the titanium clamps that generate the force to seal the hexagonal cross section, relatively hard aluminium gasket developed for TESLA and used at TJNAF and other accelerators. The System is developed to be suitable for use in SRF Clean Rooms. Results of particle counter readings during bolt and clamp installation and superfluid helium challenges to the sealed flanges are discussed. Results of a half-size clamp that could seal a soft aluminium gasket and the attempt to seal a gasket made of niobium are also discussed.

INTRODUCTION

Hyperboloid LLC designed, developed and tested the High Force Spring Clamp System characterized in Patent US 9756715 [1] that is a solution to this HBIR topic. The patent is held by Thomas Jefferson National Accelerator Facility (TJNAF).

This work validated a System that removes the greatest source of particle generation in the Superconducting Radio Frequency Cavity assembly clean room – the bolt and nut fasteners – and substitutes highly sprung "C" shaped spring clamps that may be thought of as robust Binder Clips. The clamps were installed inboard of the bolt holes of an existing flange of a Research SRF Cavity. The Cavity and parts, cleaning support, Flow Hood Facilities and Testing were supplied by TJNAF§. The Clamps were successful, established a vacuum tight seal challenged by superfluid helium, at 2 K, during two individual test cycles.

THE CLAMPS

The Prototype Clamp

The Prototype Camp was a proof of concept at the outset of the project. It formed a room temperature, helium gas leak tight seal on our assigned research cavity, RDT-05. As in all future tests, the opposite flange was sealed using standard bolts. This test proved the clamps produced the predicted high force necessary to crush a hexagonal section, high yield point, 5754 aluminium (In the US: 6060-T66) alloy gasket [2][3]. This gasket is used on cavities in US Accelerators and the International Linear Collider Project. See Fig. 1. The Prototype Test also validated the workings of the Hydraulic Clamp Openers described in the Patent.

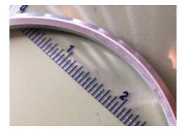

Figure 1: Hexagonal Cross Section, Aluminum Gasket.

Model 1 Clamp

Model 1 Clamps, shown in Fig. 2, with substituted hooks on the wings from the Prototype's eyelets, were installed on RDT-05 in a flow hood environment through two assembly/ test cycles. These cavity assemblies were internally clean enough to utilize the clean vacuum system of the JLab Vertical Test Area (VTA) and were pumped to a vacuum of 10-6 Torr. The cavities were mounted in one of the Area's Dewars and cooled by liquid helium, under reduced pressure, to 2 K in the Helium II or "Superfluid" state. This state is known for finding the smallest leaks. During both cycles, the readable vacuum within the cavities reduced to the 10-8 Torr range. The internal vacuum would not have remained in this range if there was the slightest leak. The Clamps (and their Hydraulic Openers) work as described in the Patent.

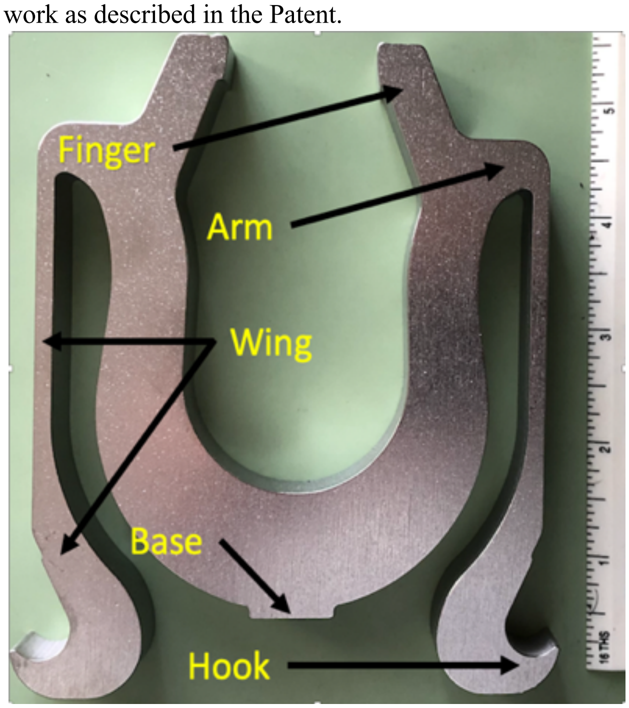

Figure 2: Model 1 Clamp.

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Model 2 Clamp

The first impression of the Model 1 Clamps is that they are large. They have to be large to generate the necessary force while not exceeding their yield stress during the installation process. Near the end of the project, we went beyond the original project scope, making Clamps with a smaller physical footprint. Model 2 Clamps, shown in Fig. 3, are about half the size of Model 1, and produce about 45% of the clamping force. They are designed to seal a non-standard, softer gasket.

Figure 3: Model 2 Clamp.

Applying the Clamps

Figure 4: Clamp Openers applying Model 1 Clamps.

Like when using a Binder Clip, the clamps are initially sprung open beyond their final clamping state. Hydraulic Clamp Openers substitute for fingers. The clamps are moved over their positions on the flanges, in opposing pairs, with about 1 mm total clearance, minimizing particle generation from rubbing as shown in Fig. 4. When the hydraulic pressure in the Clamp Openers is released, the clamps' finger tips close the clearance gap to the flange and apply their remaining, substantial spring force to press the flanges together and crush of the gasket. Additional pairs of clamps fill the remaining 10 positions on these flanges, achieving the required gasket crush.

DESIGN

Force Required

The spring clamps must be able to apply the correct seal-maintaining pressure after the aluminum gasket is crushed. RDT-05 has flanges and seal rings identical to those used for the 3 inch bore LCLS-II Cryomodules. Using a hydraulic press to press samples of these gaskets, we found the force to produce a ~1.0 mm wide crushed zone on the contact edges of the gasket. The zone is identical to that made by 12 bolts torqued to the standard 31 lb.-ft. The total force applied by the press was 14560 lb. Spread to 12 clamps, the force is over 1200 lbs. each.

Material

The spring clamp' material has to stay within its elastic limit, and not yield during clamp opening to the .180 inch necessary to generate the "bolt" force plus clearance of about 1 mm. The material chosen for the clamp is stock thickness, 5/8-inch thick, 6Al4V Titanium plate. It has the high 120,000 psi yield strength and lower $17x10^6$ psi modulus of elasticity to allow the clamp to be opened by about ¼ inch without exceeding yield stress.

Two force, material strength criteria were used for calculations for the Prototype Clamp and Model 1 Clamp:

1. When clamping the flanges against the crushed gasket, the Clamp, still sprung open by about 0.180 inch, had to produce the necessary 1200 lb. force.
2. When "sprung" to a larger gap to create a non-rubbing clearance over the flanges before any gasket crush, no active region on the Clamp can exceed, say 95%, or 114,000psi, of the Titanium Yield Stress of 120,000 psi.

Calculations and Validation

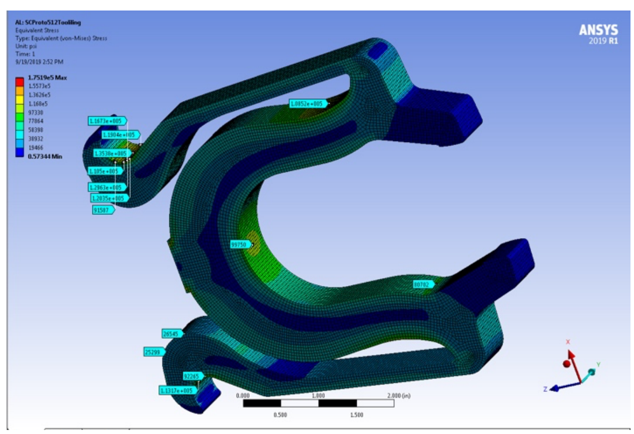

Figure 5: Model 1 Clamp's ANSYS Stress Results.

We used ANSYS to iterate the design of the Clamps so that they full fill the above criteria. An ANSYS stress result is shown in Fig. 5 with stresses not readable, but colors showing the stress distribution. We allowed bending stresses higher than our criteria in the stress concentration zones of the inner surfaces of the hooks. Yielding near the surface of this ductile material spreads the stress to a greater surface area and no failure is encountered.

We shaped the clamp to flange contact surface to a 0.50-inch R. The contact does leave a permanent foot-print mark on the flange (as does the bolt head or nuts).

We tested a first example of the prototype clamp, with load cells, over a material thickness that mimics the research cavity flanges. The force generated by the clamp matched the ANSYS calculation.

The clamped flanges remain held against one another with enough preload such that normal handling and cryogenic cycling does not break the seal. Force from the clamps does not change substantially due to cooling to 2 K. The dimensional change is about - 0.0012 inches. At the clamp spring constant of 7.3 lb./ .001 inches, the change in force is 9 lb. out of 1200 lb., which is insignificant.

Clamp Opener Design

Patent US 9756715 describes the Clamp Opener which we successfully designed and developed into hardware. The design of the Opener, shown in Fig. 6, has these criteria:

1. Work with minimal use of axial distance. The opener, must avoid interfering with the structures at the ends of the cavity.
2. The clamp and the opener have to be activated from a zone that is radial from the clamp, as in the Patent.
3. Most of the opener's working parts, that may generate particles, should be "cloaked" within an isolated enclosure.
4. A minimum of working parts of the opener should be outside the cloak and should generate minimal particles when rubbed.

Figure 6: Clamp Opener.

The clamps are opened by about ¼ inch by two balanced moments created by pull on the two hooks (or eyelets for the prototype) at the ends of the wings by Stirrups hinged to the body of the opener. The required push is supplied by a hydraulic piston in the body of the opener against the flat base of the clamp.

Several features were built into the Clamp Opener to make the clamping process easier to accomplish in the clean room environment. A set of gears synchronize the stirrup angle orientation. A set of rubber bands between the stirrups counter the drupe of the lower stirrup from gravity and make the stirrup set stable at either the open or closed position. A pedal operates the stirrups. All features are within the shroud, isolating any particle generation from the clean room environment at the cavity position.

To minimize costs, the shroud's rigid enclosure was made from a combination of consumer drink bottles with nylon bagging material extending the shroud to near the floor of the flow hood. Joints are sealed with vinyl tape. The flexible membrane between enclosure and the opening/ closing stirrups is made of nylon bag material shown in Fig. 7. This non-particle shedding material is used in the SRF industry to "bag" cleaned items.

Figure 7: Opener Stirrups, Piston & Membrane.

The Clamp Openers are mounted to Frames made with the 80/20 aluminum System with two fixed casters at the front of their bases and one swivel castor at their rear, as shown in Fig. 8. With a few iterative movements of the Frame Base on the floor, the two clamps can be positioned to move into their opposing positions. An outside crank and in-shroud screw in the upper 80/20 frame allow micrometric adjustment of the height of the opener head so that the clamp's gap clearance may be split, avoiding rubbing as the clamp is placed, stopping against the flange's tube. Release of the hydraulic pressure on the piston engages the opposing clamps on the flange pair.

Enerpac is the 10,000-psi rated hydraulic system used in the Clamp Opener System. Prototype and Model 1 Clamps, needed about the full 10,000 lb. generated by the 1 square inch area piston to open the clamp fully. We used Enerpac smallest hand pump. The hoses and fittings between pump and pair of hydraulic cylinders are all standard, 10,000 psi rated, Enerpac hardware.

In production service, the pedal driven feature operating the stirrups and the hand driven hydraulic pump would be replaced by electric actuators and a motor driven pump with electric valves respectively. Both could be voice activated for ease of use in the clean room.

USING THE CLAMP SYSTEM

Flow Hood and its Features

Our research was confined to an 8-foot x 8-foot Flow Hood with attached 4-foot-wide gowning area. This restriction fulfilled all our needs and at the same time had the advantage of making the research independent of Production Cryomodule activity at TJNAF.

The Flow Hood was equipped with a Solair 3100 Particle Counter. It was set to count up the particles inducted into its 1-1/2 suction head every 10 seconds and then recording the sum for a particular date and time, to the second. Downloads of the data were analysed using an Excel spread sheet. Photographs and their time stamps from an I-phone allowed matching the particle counts to the activities. Note that particle counting is a non-standard process, subject to where the suction head is placed etc. We are not experts, encountering only a few cycles to give us experience.

The Flow Hood was also equipped with an ionized nitrogen gun. Ionized nitrogen streams release particles from surfaces and flush them to the flow hood's downdraft. While monitoring the particle counter, when gowned in the flow hood, we washed down the curtain walls, our "bunny" suit and gloves, and any parts that emitted particles. Sometimes the parts were also washed in isopropyl alcohol and then nitrogen flushed.

Particle Generation Results

On Model 1 Clamp's first sealing cycle, of clamps on the top flange and bolts on the bottom flange, the data indicated about an equal integrated particle count for both bolts and clamps. This was early in the learning curve for flow hood use and all activity included a particle count "noise level". Clamp assembly took longer than bolting. Bolting had higher spikes in the counts indicating a greater ultimate particle contribution to flange sealing. Particle counts of bolting assembly from the second cycle were lost during a COVID-19 hiatus.

Particle counts were also taken during assembly using bolts on the bottom flange and assembly using Model 2 Clamps on the top flange. For this case, with more experience on our part, an integrated particle count was recorded of 76,000 for bolting and 6,000 for clamping, substantially different from the Model 1 Clamp result, and more what would be expected for Bolts vs. Clamps.

Attempts to reduce Particle Generation

We electropolished six of the Model 1 clamps for use in Model 1's Second Assembly Cycle, with the object that fewer particles would be generated when contacting the Stirrups. The six electropolished clamps generated 2900 particles while the six non-electropolished clamps generated 1700 particles during the assembly. Conclusion: electropolishing the clamps is not beneficial.

To find out if the surfaces of the Stirrups could be coated with lower particulate generating materials. We performed a crude test of 4 anti friction coating samples from BryCoat Co. as well as testing Vinyl Plastic and a Urethane Varnish Coating. We rubbed each material against a fresh surface of a titanium clamp with 20 strokes while above the particle detector head. The results show that BryCoat's Titanium Aluminum Nitride (TiAlN) is just as good as the aluminium block that the Stirrup is made from. All other materials were worse. Conclusion: the original material choice for the stirrups was a good choice.

OBSERVATIONS ON THE USE OF BOLTS

Particles from Bolting May Not be in Cavities

Our observation is that assemblers of cavities use very effective mitigations to keep the insides of cavities free of particles due to bolting. They initially use shop-type spring clamps covered in rubber gloves, that generate few particles, to bind flanges and their gaskets together in cavity string assemblies before any bolts are applied. They follow by adding only two bolts per flange pair and lightly torquing them to close the contact edges of the gaskets, further assuring a particle free seal. They follow-on with full bolted assembly. Any particles from bolting contaminate the fixturing and clean room, but not the insides of the cavities.

Secondly, the geometries of the bolts trap most of the generated particles within the threads or under the bolt or nut heads so they are not released during assembly. It was observed that the sockets of socket wrenches trapped particles when nuts were tightened beneath vertical studs. When the wrench sockets were turned over, the particle counter noted a release from the sockets.

Labor Considerations

Conversations with the assembler personnel reveal that the high forces involved in using torque wrenches take a physical toll. Many of the personnel require re-assignment to alternate "light" duties after working in the profession for some time. Their hand, wrist, carpal tunnel, elbow and shoulder joint problems may become permanent arthritis in later years. The story of this toll remains within the assembler community and is not the subject of academic papers on the advances in SRF.

The touch labor associated with cleaning the bolts, nuts and washers is an un-appreciated assembly cost. In addition to ultrasonic cleaning, the parts require a lengthy, final "blow-down" with ionized nitrogen in the sequestered area of the clean room with a particle counter and direct exhaust.

Overall Observations

Bolts in SRF applications are used near their ultimate strength. Large forces are involved; box-end wrenches or sockets deform the bolt heads or nut flats and actually bind to them and then have to "forced" to release, generating particles. Torquing the nuts always has a stick-slip chatter. Chatter means materials are sliding over one another, welding and breaking free, inherently producing grit. As an editorial comment, using bolting to seal cavities is the antithesis of an operation meant to take place in a clean room.

MODEL 2 – THE SMALLER CLAMP

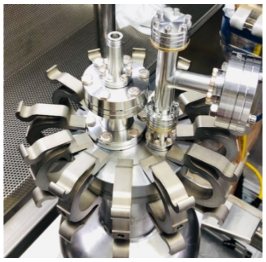

Figure 8: Model 2 Clamp Assembly.

Figure 9: Model 1 Clamp Assembly.

The 29,000-psi yield strength of the standard aluminium gasket is a likely candidate to change to 1100 Aluminum with its 11,000-psi yield strength, reducing the force needed to crush the gasket edges. We found annealed 1100 Aluminum parts with a gasket-like, 120° edge would obtain the ~1 mm crush zone with a 560 lb. force per clamp. We designed the Model 2 Clamp to generate that force and had 14 of these clamps made along with adaptation parts for the Clamp Opener's Stirrups. The clamps needed only about 4000 lb. of hydraulic force to open enough to clear the flanges. The reduced footprint of Model 2 Clamps assembled on a flange pair may be see in Fig. 8, printed at about the same scale (at the flanges) as Model 1 Clamps assembled on a flange pair in Fig. 9.

Niobium Gasket

Acting on an incorrect calculation, that the aluminum gasket may slide upon cool-down because of low compression force, we abandoned the 1100 aluminium consideration and chose pure Niobium for the gasket. It is soft, with a yield strength of 5,000 psi and matched the coefficient of thermal expansion (CTE) of the flanges, a further benefit. The seal leaked at the 10-7 cubic centimeters of He per second level. We did not have funds or time to investigate the use of the Model 2 Clamp with a soft aluminum gasket.

CONCLUSIONS

Hyperboloid LLC proved that High Force Spring Clamps can seal SRF Flanges superfluid helium leak tight using the prevailing aluminium gasket ring used for many cavity sealing applications and generate fewer particles than when using Bolts.

The clamp concept is a much better match for sealing the metallic gaskets of future SRF projects because of its lower overall particle generation and the ability to use hydraulics rather than physical labor to establish seals. The clamp system also leads to potential automation in the sealing of cavity strings. Clamps the size of Model 2 would probably not be rejected by cryomodule designers. A limited amount of future investigation into soft metal gaskets could qualify the Model 2 Clamp System and its Clamp Openers as a practical advance in the SRF state of the art.

ACKNOWLEDGEMENTS

We received great cooperation from the SRF Institute at Jefferson Lab. They were able to fit requests for help into their daily production cryomodule duties with little or no delay.

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