Design and Development of Sealing Mechanism for Gaseous Medium Cryogenic Safety Valve for ISRO Launch Vehicle Application

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Abstract

Safety valves are most commonly used in aerospace, oil and chemical industry to prevent over pressurization of systems leading to loss of man, material and machine. Usage of cryogenic valves is very common in various launch vehicles worldwide as well as within ISRO. In aerospace application, safety valves are used to prevent over pressurization of either propellant tanks or other subsystem's like command system, roll control system and/or orbit control and stabilisation systems.

Inverted operation relief valves offer advantage of relatively higher sealing stress at operating condition in comparison to direct operation relief valves. Leakage observations in relief valves are very common and also a primary cause of failure. In contrast to pneumatically operated ON/OFF valves, seat stress in relief valves are limited and further reduces close to operating conditions.

Mechanism of sealing in relief valves could be either hard on hard or soft on hard type of sealing. Owing to better leak tightness, soft on hard type of sealing is mostly preferred for cryogenic gaseous application. Soft materials like polycarbonate, Teflon &Kel-F has good sealing characteristics, whereas the mechanical strength of these soft materials is inferior to metals and cannot be used as structural member inside valves. Lesser mechanical strength of these non-metals requires sufficient metallic support to increase structural integrity of valve seats. Soft seats are inserted into these metallic poppets after dipping in liquid nitrogen to achieve required amount of dimensional shrink followed by seat pressing and crimping using special purpose dies. Specially crimped soft seats by plastic deformation of metals helps in retaining soft seats inside metallic poppet. Ductile materials like Aluminum Bronze and AISI 321 are commonly used as poppet materials.

The process of poppet sub assembly crimping is a highly skilled operation and carried out after ensuring low temperature clearances, mating point radius/chamfer and smooth edges for die travel. This paper discusses the crimping of a cryogenic safety valve poppet sub-assembly with soft seat as polycarbonate and metallic poppet made up of Aluminum Bronze. Observations during crimping and issues related to ineffective crimping along with NDT evidence are discussed in detail. Crimping process qualification and advanced NDT screening of every crimped poppet subassembly is also presented in this paper. A comparison of load requirement during crimping by analytical approach against UTM load applied is made and a good match is observed.

Keywords: *Crimping, Safety Valve, Cryogenic, Plastic Deformation*

1. Introduction

Safety relief valves are commonly used in high pressure systems to safeguard system from over pressurization. Leak tightness of relief valve at operating conditions is a critical parameter in the design especially in aerospace as gap between operating pressure and relief valve full opening pressure is very narrow due to mass constraints in flight stages. Leak tightness of valve is a function of type of seating, surface finish of the sealing surface and seat stress. Due to design constraints, seat stress in relief valves are limited and reduces close to operating conditions. Soft on hard type of sealing is mostly preferred for cryogenic gaseous applications. To provide structural integrity of seat, soft seat is embedded into a metallic body. Although soft seat will arrest primary leakage a possibility of secondary leakage occurs through the joint between structural metallic part and soft material. One of the

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process to arrest secondary leak path is crimping in which metal lip is bend onto a soft seat to arrest secondary leak path. This paper discusses about observations and issues faced during crimping of a relief valve proto hardware poppet sub assemblyin detail.

2. LITERATURE REVIEW

Extensive research has been conducted in tube drawing process. Fundamental equations for tube drawing was developed by G. Sachs et al [1].In his study, tube drawing equation with a moving mandrel was solved for both cold-drawing and hot-drawing of thin-walled tubing through a stationary die. An analytical model using upper bound solution for tube drawing process was developed by Um et al [2]. Based on his studies many finite element models were developed by researchers. Numerical modeling of thin walled stainless steel 316L tubes were done by M. Palengatet al [3]. Effects of processing parameters on drawing stress, maximum reduction and optimal die angle were analyzed by D.W. Zhao et al [4] by using an analytical solution by strain rate vector inner product integration. Validation of finite element model for tube sinking w. r. t. drawing force and wall thickness was conducted by Maciej Pietrzyk et al [5]. An elasto-plastic large deformation analysis of ironing process was conducted by You-Min Huang et al [6] and found good agreement with load displacement relation of experiment and simulation values. Various literatures are available on tube drawing/sinking process however specific published literature on crimping of metallic poppet for soft seat retention is not available to the author's knowledge.

3. PROBLEM DEFINITION

In cryogenic stages, desired stage working and performances are obtained by actuating ON/OFF type pneumatic valves in a predefined sequence. These ON/OFF type pneumatic valves are actuated with command gas. In order to reduce the envelope of gas bottles, command gas is stored at high pressure in stages. This high pressure gas is regulated to desired command pressure using a pressure regulator and supplied to pneumatic valves. In one of ISRO's launch vehicle, gaseous helium stored at cryogenic temperature in gas bottles is used as command gas. Regulated pressure of $50^{\pm 3}$ bar is supplied to pneumatic valves via command module. In order to prevent inadvertent pressure rise at downstream of command module, cryogenic relief valve is installed in command line. Relief valve is spring loaded mechanical valve with a designed set pressure. When the system pressure reaches its upper bound pressure which is also the cracking pressure of relief valve, then relief valve vents excess pressure to ambient and restores system back to its operating regime.

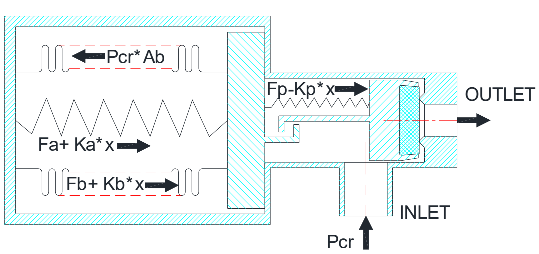

Figure 1: Working schematic of a typical Inverted operation pressure relief valve

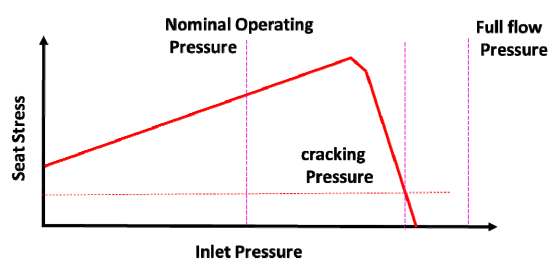

Figure 2: Variation of seat stress of inverted operation relief valve against inlet pressure

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Figure 1. shows the working schematic of an inverted operation relief valve. A similar relief valve is under development at ISRO for one of upcoming launch vehicle. There are two helical compression springs in this configuration as shown in Figure 1. The first spring is a poppet spring which provides initial seat stress for seat and another one is reference spring which decides cracking and full flow pressure. The seat stress which controls the leak rate through the valve increases in inverted operation relief valve with increase in inlet pressure. Variations of seat stress against inlet pressure is shown in Figure 2. Functional checks of relief valve are carried out at room temperature and also at cryogenic temperature. Functional checks for a relief valve include determination of Cracking pressure, Full flow pressure and Reseal pressure which is depicted in Figure 3.

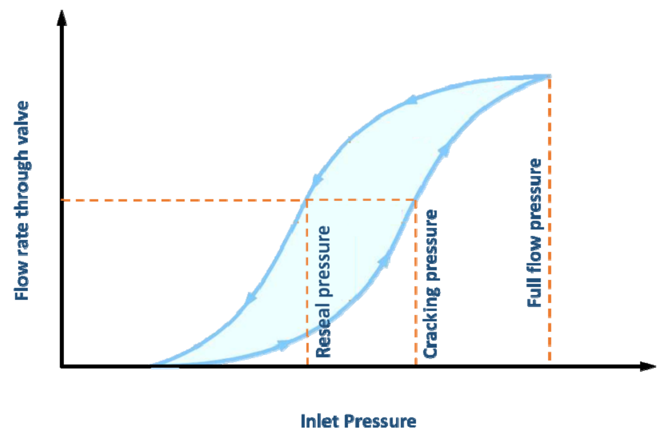

Figure 3: Cyclic functional Test pressure of typical relief valve

Cracking pressure is referred to an inlet pressure at which relief valve leakage is equal to a 0.5 sccs measured via inverted jar method in water displacement. Figure 4 shows test setup for measuring cracking and reseal pressure of relief valve. Gaseous helium is regulated to desired pressure and supplied to inlet of valve. Outlet of valve was connected to a leak tube and valve leak rate is measured using inverted jar method.

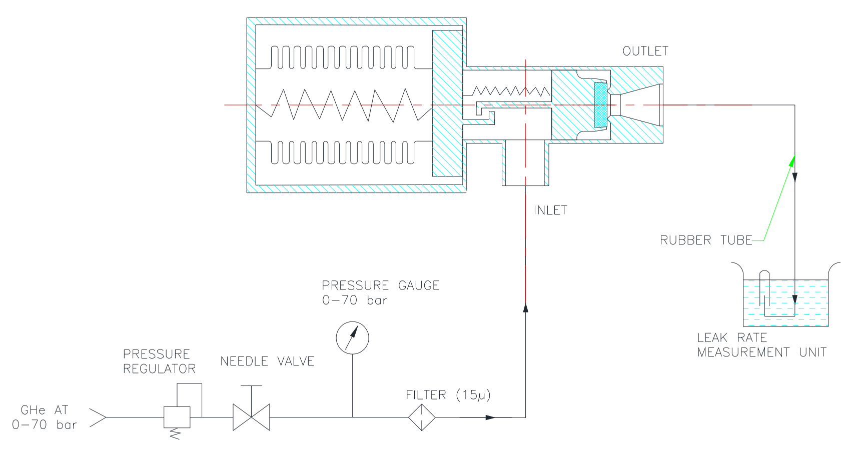

Figure 4: Test setup for measuring cracking pressure ad reseal pressure of relief vale

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Full flow pressure is defined as the inlet pressure at specified mass flow rate is discharged through valve. Reseal pressure is pressure defined as inlet pressure at which flow rate through valve is reduced to a value equal to 0.5 sccs when the inlet pressure is reduced from full flow pressure. A configuration of sealing area (poppet and seat) of valve is shown in Figure 5.

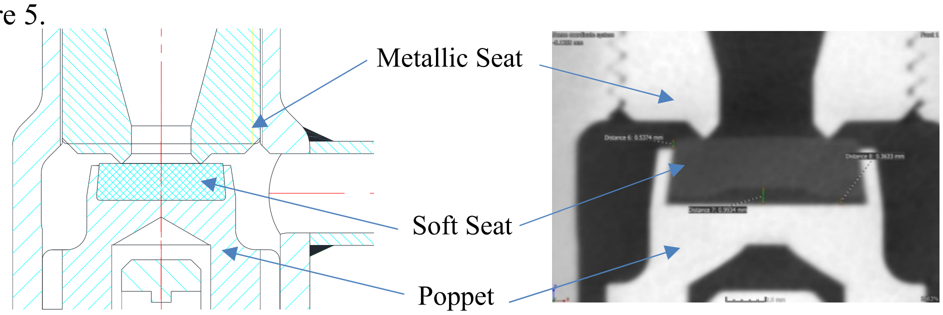

Figure 5: Configuration of Seat

Figure 6: CT image of Seat after low temperature test

During proto hardware development, multiple cyclic actuations of relief valve is conducted, i.e. Cracking pressure to full flow pressure and then to reseal pressure. Cyclic actuations tests were conducted at ambient condition and cryogenic condition. For assessing the health of valve, a repeat health check of valve at room temperature is carried out and observed that cracking pressure and full flow pressure of the valve is changed. Another hardware was tested to the same condition and found increase in cracking pressure. In order to find the root cause of problem, CT scan of hardware was taken and is shown in Figure 6. It was revealed that polycarbonate seat had bulged up leading to change in the poppet spring Initial Load. This happened due to improper soft seat pressing against metallic poppet, leading to gas entry during cryogenic test followed by expansion of same entrapped gas during ambient testing. This lead to soft seat bulging and change in cracking and full flow pressure. CT scan image of valve clearly depicts a bulging of polycarbonate seat. In order to rectify this issue in prototype hardware, mechanical seat shall be sufficiently pressed against soft seat so that no secondary leakage path is available for the gas to enter. The process of bending the metal lip for soft seat retention to obtain a leak tight joint is termed as crimping.

4. Research Methodology

4.1. Process of Crimping

Aluminum Bronze material is selected as the poppet material for soft seat retention owing toits higher ductility, compatibility with cryogenic medium, self-lubricating capability and requirement of dissimilar metals for sliding joints. Material of seat is selected as polycarbonate which has excellent sealing characteristics at ambient and cryogenic temperature. Seat is designed to have an interference fit of 200-286 µm than corresponding cavity inside metallic poppet in ambient condition. Polycarbonate seat is immersed in liquid nitrogen medium to shrink so that it can be inserted inside metallic poppet. After temperature stabilization,fit between polycarbonate seat and poppet changes to clearance fit and is smoothly inserted inside poppet as shown in Figure 7. After polycarbonate seat is inserted, the metal lip of aluminum bronze is deformed using a special purpose die as shown in figure die as shown in Figure 8.

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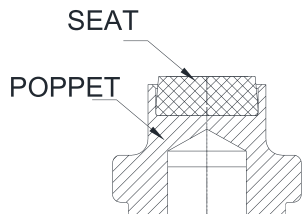

Figure 7: Seat and Poppet

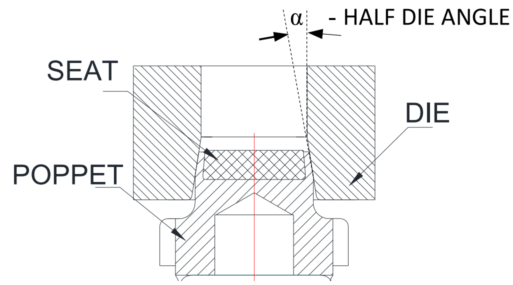

Figure 8: :Schematic representation of crimping process

The major important parameters of crimping process are the angle of crimping, surface finish of die, the die travel distance and alignment of die w. r. to poppet. Die angle is a critical parameter in determining how much the metal is pressed against polycarbonate seat. Initial angle was provided on the polycarbonate seat to ensure smooth insertion and easier bending of metallic poppet. Die angle should be more than the seat angle on polycarbonate to create a positive leak tight joint. Polycarbonate seat was designed with semi angle of 5 degree. Inorder to obtain a positive joint leak tightness final angle of metal lip after crimping should be more than that of polycarbonate seat. The semi angle of die was designed with an inner semi angle of 10º degree in order to obtain 9±1º on the final crimped poppet. Surface finish of die is important as better surface finish can reduce friction between die and poppet at the time of pressing and requires lesser load for crimping. Improper alignment of die w r to poppet can cause non uniform loading of poppet which in turn cause secondary leak path. Die travel distance is controlled to limit the amount of deflection of poppet on to soft seat so that metal will not pierce inside soft material. The plastic deformation of poppet and seat make the valve a leak tight joint.

4.2. ANALYTICAL SOLUTION

Governing equations are derived using theory of plastic deformation. Following are the assumptions made for analytical validation.

- Materials are isentropic and homogenous and free from defect
- The deformation of die, loading pin and housing are neglected and considered rigid bodies
- Tube sinking equations are used because of its similarity to crimping process.
- Volume is conserved before and after crimping.
- Resistance offered by polycarbonate seat is neglected as it can flow easily under application of heavy loads.

For analysis, the metal part is considered as a tube of fixed diameter drawn through a die. Crimping process is considered analogous to tube sinking process. The difference is that die moves forward and deforms the metal tube in crimping while in tube sinking the tube is drawn through a die.

Drawing stress in tube drawing is given by [7] and are shown in equation (1).

$$\sigma = y' \left(\frac{1+B}{B}\right)\left(1 - \left(\frac{Af}{Ao}\right)^{B}\right) \quad (1)$$

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$$B = \left(\frac{\mu 1 + \mu 2}{\tan\alpha - \tan\beta}\right) \quad (2)$$

an elastoplastic model of Aluminum bronze was used for the analysis

$$\sigma = k\ \epsilon^{n} \quad (3)$$

y' mean flow stress is given by

$$y' = \frac{k\epsilon^{n}}{1+n} \quad (4)$$

where, = Tube drawing stress

= Coefficient of friction between die and poppet

= Coefficient of friction between poppet and inner mandrel = 0

=Half Die angle

=Half mandrel angle = 0

=Final Area of Tube

=Final Area of Tube

4.3. Experimental Validation and Crimping

For experimental validation of analytical solution, six poppets were realized with Aluminum bronze material(C63200) and seat was realized with polycarbonate material. The outer diameter of crimping lip is 15 mm and inner diameter is 13 mm as shown in Figure 9. Crimping die is made up with a harder material (SS MDN 59). A fixture was designed to hold poppet and guide the die inside as shown in figure 10. A stopper was added to prevent bulging of polycarbonate seat during crimping process. Loads are transferred to die using loading pins. Load is applied to the loading pin using a universal testing machine. This subassembly fixture i.e. along with poppet and seat is mounted in UTM and load is applied at a controlled speed of 1mm/ min. A load cell of 5T was attached to UTM Which gives the load vs deflection of die.

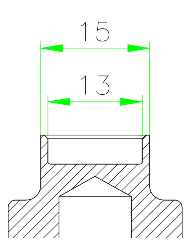

Figure 9: Cross section of poppet

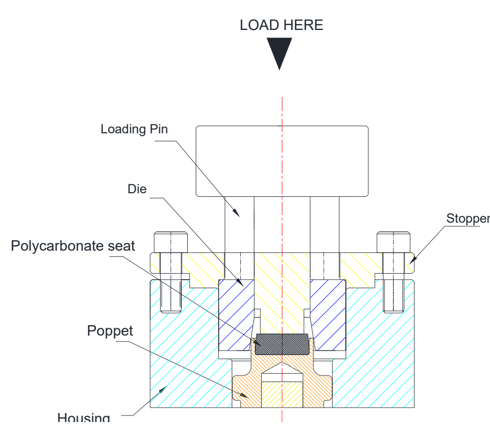

Figure 10: Schematic representation of experimental setup

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The maximum travelling distance of die is limited by the mechanical stopper available at the bottom of Housing. This is done to safeguard poppet from over bending. A sudden rise in load can be observed when the die touches bottom mechanical stopper as the load will be transferred to housing. To obtain uniform surface and angle on poppet after pressing die was rotated by 180º and process of loading was repeated.

5. Results and Discussions

Crimping fixture is loaded in UTM machine and crimping load is applied gradually at a controlled rate of 1mm per minute. A limit of 2000 kg for the load and a 3.5 mm limit for the deflection were set as an emergency stop for the UTM. The resulting load vs deflection graph is shown in Figure 11. The crimping commences with gradual increase in the deflection with increase in the load applied. Then a sudden increase in load is observed as the die makes contact with the mechanical stopper. Once die makes contact with mechanical stop,load is retained at the same level for an additional 5 minutes for stabilization and to minimize the effect of spring back. Subsequently, the load is gradually withdrawn. In order to obtain a uniform crimping and reduce the effect of misalignment of die, the crimping procedure is repeated by rotating the die by 180º. Figure 12 shows the load vs deflection graph for re-crimping. Table 1 below shows the consolidated crimping load in each pass and resultant crimping angle.

Load required for crimping of soft seat is calculated using formula given in eqn. (1). The coefficient of friction between die and aluminum bronze poppet (μ= 0.45. Half die angle =10º. Mean flow stress y' =318.2 MPa considering an average strain of 10% during cold working is assumed for the analysis. Total crimping load is calculated by multiplying initial area with drawing stress given in eqn. (1).

Table 1: Comparison of experimental Crimping load against theoretical crimping load

Sl No	Poppet No	Calculated Load (Kgf) Min.	Applied Load in UTM (Kgf)	Die Travel in first crimping (mm)	Load applied in second crimpin g(Kgf)	Die Travel in second Crimping (mm)	Achieved angle
1	Poppet 1	581.75	756.00	2.44	580.00	0.77	8º40'
2	Poppet 2	595.82	792.00	2.75	700.00	0.76	8º40'
3	Poppet 3	557.12	756.00	2.81	632.00	0.83	8º30'
4	Poppet 4	548.59	816.00	2.82	704.00	0.80	8º40'
5	Poppet 5	554.09	772.00	2.74	710.00	0.80	8º40'
6	Poppet 6	541.83	560.00	2.73	464.00	0.76	8º30'

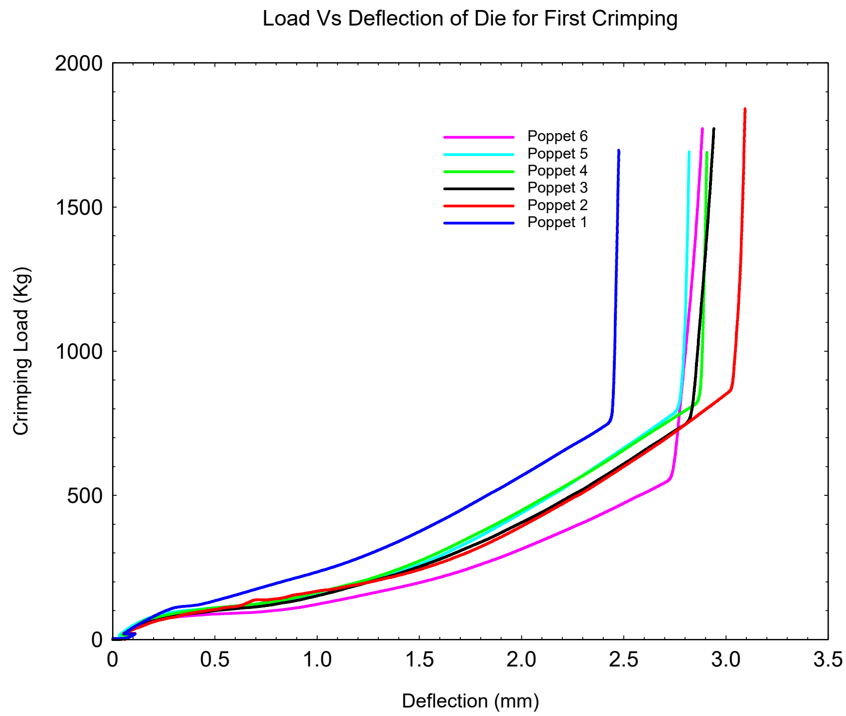

Figure 11: Load vs deflection of die in first crimping.

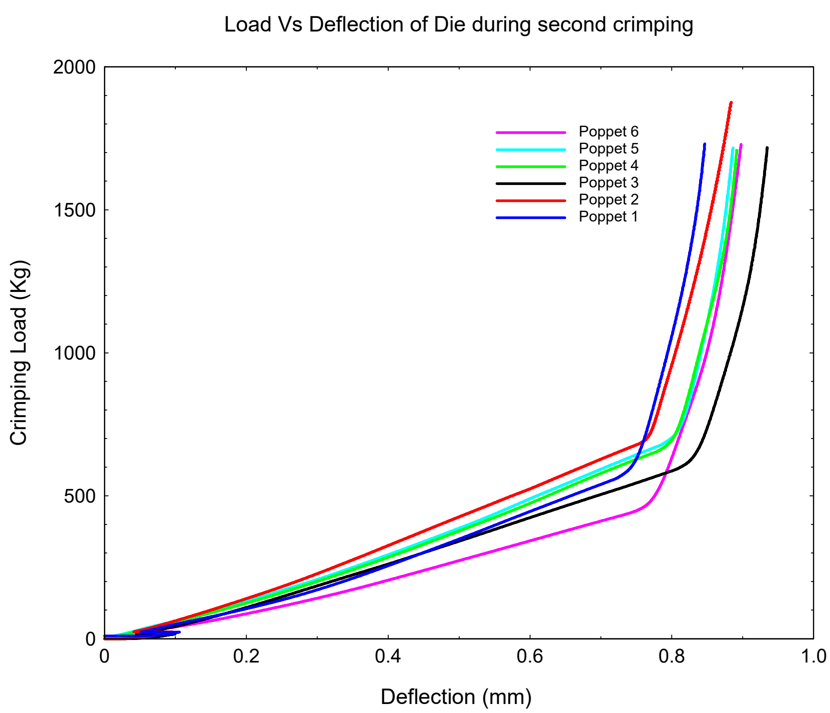

Figure 12: Load vs deflection of die in second crimping.

Table 1 shows the load applied at crimping is more than calculated load. During first crimping the applied load was found to be more than 31% of calculated average load.

Reasons could be due to nonlinearity of materials, friction between die and metallic poppet or geometric misalignment of poppet and die. The error was found to be reduced to 12% during second crimping. Average crimping angle achieved is 8º30' against expected value of 9. This is due to spring back effect. Angle provided in polycarbonate seat is 5 degree. So always a positive compression is ensured in polycarbonate seat by metal lip tocreate a leak tight joint.

To test leak tight joint each poppet was tested at low temperature and ambient condition for cracking pressure, full flow pressure and reseal pressure. CT scan image of poppet and seat was taken before and after test and is shown in Figure 13. It is evident from CT scan image that no bulging or gap at bottom side of seat was noticed. Also no bulging of soft seat was found on all six poppet subassemblies.

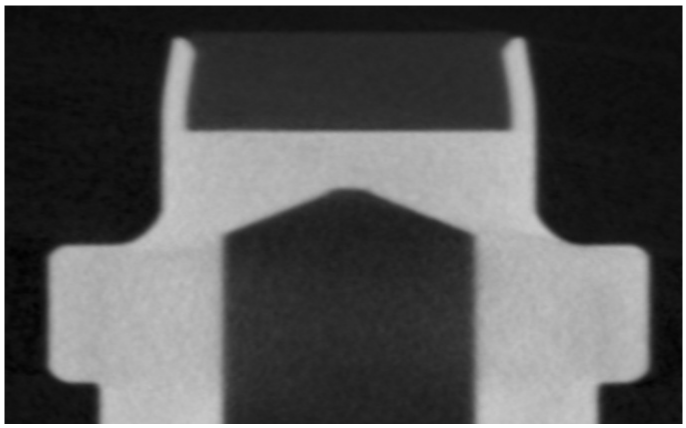

Figure 13: CT image of newly crimped poppet and seat after low temperature test

6. Conclusions

This paper provides information about design considerations and issues faced during crimping process of a cryogenic safety valve poppet subassembly for soft seat retention. A comparison of load requirement during crimping by analytical approach against UTM applied load is presented. Reasons for difference from analytical to experimental test is understood and listed.

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