Thermo-mechanical induced deformation simulation studies for metal gaskets for UHV application

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Abstract. In vacuum technology, metal gasket seals are extensively employed to achieve a UHV with reduced contamination considering the pressure and temperature variations as it performs a static seal between two stationary members of a mechanical assembly. The optimum sealing is attained over the balancing of the forces effective, which are function of temperature, governs the surface deformation for the metal gasket seal follows into degradation in the leak tightness at elevated temperatures. The prime component exerting the most deformation force over metal gasket seals, gasket seating force is a constant value generated by the bolting of the stationary members of a mechanical assembly. The paper address to metal gasket seals, copper and aluminum, behavior under thermo-mechanical load is analyzed (simulation), with ANSYS platform, workbench. The major concern is to investigate the typical deformation behavior as a function of thermal variation, baking/cooling. For copper and Aluminum gasket seals, 16mm to 250mm internal diameter, exposed to pre-established gasket seating force under wide temperatures range. The deformation, average and the deformation range, observed to move in a very specific manner and runs to a wide range for a given material and size. The data reported here deserves to be substantial enough to establish the prediction of thermal behavior of metal gasket seals for standardization.

1. Introduction
Invented by Austrian engineer Richard Klinger about 100 years ago gaskets are employed to achieve static seal between two stationary members of a mechanical assembly, harboring surface imperfection induced probable leaks, under extremes of temperature and pressure. Metal seals are the crucial components in UHV systems for achieving the required leak tightness and to avoid any kind of catastrophe for optimum performance[1]. The mechanical behavior between the knife-edge-type flange and gasket material involves various types of complicated mechanisms such as elasto-plastic deformation, large deflection, thermal creep, and contact-friction. Metallic gaskets seals are generally used where applications in which joint might be exposed to UHV conditions with baking requirements and higher leak tightness over wide range of temperature operation. Also in addition, these metal seals exhibit low degassing, permeation and long term radioactive resistance. The metal seal capable of withstanding very high temperature is possible if the joint is designed to yield locally over a narrow location with application of bolt load. UHV systems in general use Aluminium and Copper as sealing materials over wide range of temperature due to their better mechanical properties and low outgassing rate. Metal gasket sealing, in particular the Copper and Aluminium materials are

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the choice of experimentalists for attaining the suitable leak-tightness which are widely used in vacuum systems in various applications like laboratory plasma vacuum systems, and many other industrial vacuum processing production systems. Some typical applications like large vacuum systems like fusion devices, stellarators, accelerators etc will use custom designed seals based on required dimensions. On applying a load, bolting of the flanges containing the metal gasket holds the sealing to attain the required tightness. The bolting of flanges exerts mechanical force over the gasket, induces the local surface deformation, in case of knife edge flange system. An established experience reveals baking, as an integral part of number of experiments to withstand the degree of cleanliness, degassing for vacuum, adds to the gasket a nonzero deformation. The deformation information in terms of magnitude and dynamics is highly significant for gasket designing and selection for the specified experiment with a satisfactory performance. Attempts to understand the mechanical loading over gasket, mathematical modeling [2,3], based on theory of elasticity, have been made to understand the contact stress distribution for high pressure pipeline along with rotational flexibility [4], holding nonzero probability. H.Fend has given attempt to reduce the seating force on metal seals by modified mechanical design of seal and the same were validated with experiments for different kinds of UHV applications[5] and further this analysis revealed that the seating force applied has been reduced to 50% in comparison with regular metal standard CF design and less material usage.

The present study, simulation attempt has been carried out with standard mechanical metal gasket of Copper and Aluminium seal materials over the wide range of dimensions and thermal baking conditions. The thermo-mechanical load on metal seals which in similar to bolt tight gasket in a two side knife edge flange assembly deployment under variable backing conditions, for range gasket material and sizes are analyzed.

| Standard CF range | D1(mm) | D2(mm) |
|------------------|--------|--------|
| 16               | 16.2   | 21.2   |
| 35               | 38.0   | 47.7   |
| 63               | 63.6   | 82.2   |
| 100              | 101.7  | 120.2  |
| 150              | 152.5  | 171.0  |
| 200              | 203.3  | 222.0  |
| 250              | 254.0  | 272.5  |

The gasket and flange system under operation are exposed to a complex force assembly having peculiar formation as shown in Figure 1. The acting forces are balanced as to restore the highest leak-tightness achievable. The total force compressing the gasket to create a seal, mechanical loading is referred as seating force. The mechanical characteristics exerting pressure against the gasket to unseal gasket joint and against the flanges holding the gasket in place, named hydrostatic end force. The
mentioned forces are indicative of the mechanical loading, creates deformation as effective over in the
sealing assembly. The temperature also adds to the deformation, creates thermo-mechanical effects
induces the promotion of "creep relaxation", a permanent strain or relaxation quality of soft materials
under stress. As a rule, the higher the temperature, the more critical becomes the selection of the
proper gasket. The assurance of perfect sealing will be given by the nonzero residual force, difference
of gasket seating force and hydrostatic end force.

2. Simulation and Analysis
The simulation for gasket deformation under thermo-mechanical load is performed on ANSYS
Workbench software followed by IDL analysis of the data for the deformation studies. The applied
load in the form of uniform distributed torque is assumed in all the analysis procedure. The details of
the adopted procedures are given in the following.

2.1 Gasket design
Standard metal gasket design/dimension was incorporated in the simulation as per Table 1. Imagery
dimensions were considered for both copper and aluminum. The details of the structural material
Copper and Aluminum properties of which the gaskets are made up of are employed, as per the Table
2, were the standard ANSYS library which is found to be constant.

| Properties            | Aluminum | Copper  |
|-----------------------|----------|---------|
| Young’s Modulus       | 7.1 e+10 Pa | 1.1e+11 Pa |
| Poisson’s Ratio       | 0.33     | 0.34    |
| Density               | 2770Kg/m³ | 8300Kg/m³ |
| Thermal Expansion     | 2.3e-5 1/°C. | 1.8e-5 1/°C. |
| Tensile Yield Strength| 2.8e+8 Pa | 2.8e+8 Pa |
| Compressive Yield Strength | 2.8e+8 Pa | 2.8e+8 Pa |
| Tensile Ultimate Strength | 3.1e+8 Pa | 4.3e+8 Pa |

2.2 Solid and finite element (FE) model of Gasket
The thermo – mechanical structural analysis of metal gaskets was carried out using finite element
package ANSYS work bench [6]. A gasket is deployed in a flange assembly (considered to be CF
type) offers a two side knife edge contact. When bolted the gasket experiences bolting load via knife
edges at a well defined confined surface. This enhances the deformation probability as the effective
area decreases.

![Fig. 3. The mesh model created in ANSYS](image1)

![Fig. 4. Al and Cu seals deformation](image2)
The symmetric circular gasket with symmetric loadings (defined connection area), is modelled for coupled thermo mechanical structural analysis. The first demanded for simulation is for a mesh model, shown in Figure 3. The differential meshing is considered for the gasket as the criticality of the physical phenomenon is unevenly distributed. The area of contact where the knife edge is effective will be expected to exhibit higher deformation probability. Some images of 35CF flange Al and Cu seals are shown in Figure 4 for deformed shape due to mechanical loading after removed from the UHV baked systems.

2.3 Boundary and loading conditions
The next step for the simulation is to set the environment parameters over the 3D geometry in to the when imported to the simulation section of ANSYS. The assumption was taken in order to check the standard practices followed in UHV laboratory systems such that the validation of the analysis can be done.

2.3.1 Mechanical Loading.
The seating force which is applied on bolting is the primary binding of the assembly, induces substantial deformation. The binding force is calculated \[ F = \frac{\pi}{4} (OD^2 - ID^2)Y - \frac{\pi}{4} OD^2 P - \frac{\pi}{4} (OD^2 - ID^2)P_m \] \( (1) \)

As per equation 1, OD is outer diameter, ID inner Diameter, Y is minimum Seating stress, P maximum Internal pressure, m is Gasket factor which is ratio of contact pressure with contained pressure for the applicable seal materials. The gasket designer use the above formula for the seal design practices. A nonzero magnitude of residual gasket force ensures the leak tightness for the assembly. The calculation of seating force was carried out by a dedicated IDL codes so as to have the precise values of the force magnitude acting when flanges are bolted.

2.3.2 Thermal Loading.
The thermal loading is a potential contributor to significant deformation over the gasket. The simulation considers whole volume of the gasket on a constant and uniformly distributed temperature, pre decided input. As mentioned, for our studies the mechanical loading is constant all across the observation with a range of thermal loading, temperature range 10°C to 250°C. The temperature range serves different operating condition of the gasket, till backing or degassing, common practice for UHV applications.

Fig. 5(a). Deformation with 35CF Al @100°C seal
Fig. 5(b). Stresses for 35 CF Al seal @100°C
2.4 Simulation output
Simulation was conducted to know the deformation information for different gasket size as a function of time and material. Figure 5 and Figure 6 shows the typical output from the simulation made. Figure 5(a) describes the Al seal which has gone under stress with 35CF standard flange gasket load (seating stress of 35kN) conditions and with applied temperature of 100°C. The deformation with knife edge dislocation mechanism are shown for reference. Figure 5(b) describes the stress levels on the deformed shape with Aluminium seal. In figure 6(a) deformation levels of 150CF Al seal with 230°C was shown with applied seating force of 285 kN. Similarly in figure 6(b), deformation level was shown with 100CF Cu seal with constant seating force 288 kN and at 150°C.

3. Results of the analysis
The Thermo-Mechanical load analysis cases for Al and Cu metal seals for range of inner diameter (ID) have been considered for the quantification of deformation. ANSYS simulation provides the maximum and minimum values for deformation. In order to compare different dimensions and material of gasket average deformation and the deformation range at a particular temperature are measured. This allows uniform and easy comparison between different cases. Figure 7 and Figure 8 shows the average deformation over the temperature scale for different ID for Al and Cu.

Fig. 6(a). Deformation with 150 CF Al seal @230°C
Fig. 6(b). Deformation with 100 CF Cu seal @150°C

Fig. 7. Average Deformation Al seals Over wide temperature and different
Fig. 8. Average Deformation Cu seals Over wide temperature and different
The average deformation is plotted on the y axis (log scale) as a function of temperature (°C), exhibits that the change in the average deformation is higher at lower temperature with respect to the higher side of the temperature range. Figure 8 is shown with the average deformations analyzed with reference to the measured values in range of temperature from 10°C to 250°C temperature with Cu gasket seals which are regularly applied in UHV systems. Similarly for Al gasket seals deformations analysed with are shown in figure 8.

4. Summary
Thermo-mechanical analysis of the metal vacuum seals is carried out with standard laboratory dimensions regularly used in UHV applications. The analysis for Cu and Al seal materials has been carried out with uniform seating load and wide temperature range from 10°C to 250°C with different flange seals like from 16 CF to 200 CF compatible flanges. The simulation analysis revealed that the deformations at the early temperatures are quite significant when compared with the higher temperature range in both materials with standard applied seating load on to the seals. The analysis procedure will be helpful for the estimation of deformations in working conditions like mechanical and thermal loads.

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