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Exploring Nonlinear Behavior of Gasket Joints in DEF Dosing Units through Finite Element Analysis

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Abstract:

Gaskets serve the crucial function of maintaining a durable seal within 2fixed components within a mechanical structure, even when subjected to varying pressures and temperatures during operation. Gasket joint is necessary in many mechanical systems to form a leak free joint. DEF dosing system is one of the examples where gasket joints are used to prevent exhaust gases leaking before going through SCR. Gasket joint requires certain minimum pressure to make leak free joints. If the gasket pressure goes below the pressure of the internal fluid in the assembly, then there are chances of leaking the fluid out. If the gasket pressure is increased by applying high bolt preload, then there may be chances of yielding of the flanges or this may cause damage to bolt/nut threads. So, there must be optimum gasket pressure in the assembly. The gasket pressure gets affected by many parameters. The present paper aims to avoid leak in case of gasket joints.

There are number of parameters which affects the performance of the gaskets e.g. bolt preload, bolt tightening sequence, internal pressure, temperature of internal fluid, creep of gasket etc. Different analysis has been carried out to check effect of allthese parameter on the contact pressure at the gaskets joint. Initial gasket pressure was mainly controlled by bolt preload/torque. The effect of bolt torque on the performance of the gasket joint assembly was studied. A dimensional nonlinear finite element analysis was carried out on the gasket joint and sealing performance was correlated with experimental study.

Different geometric configurations are studied at different bolt pre-load levels. Effect of bolt torque on gasket pressure as well as other components of the assembly was studied. The best configuration which gives gasket pressure above minimum required to maintain leak proof joint and with no yielding in the assembly has been recommended.

Keywords: FEA Modeling, DEF Dosing unit, Gasket Joint, Nonlinear Analysis.

1. Introduction

Pipeline systems & pressure vessels frequently use gasket flange couplings. The gasket is very helpful in designing leak free mechanical system. In actual condition it is nearly impossible to have perfectly mated flanges and to maintain an intimate contact between flanges throughout the extremes of operating conditions. It could be because it's challenging to keep incredibly smooth flange finishes throughout handling, assembly, and operation-related erosion &corrosion of the flange surface.

Therefore, a sealing element in such mechanical systems is made of inexpensive gaskets. Generally, gaskets work by using external pressures to push the gasket substance into the gaps between the mating surfaces in order to create a seal [1].

In this study, we investigate gasket joints within the DEF dosing system of a diesel engine exhaust system. Diesel Exhaust Fluid (DEF) serves as the essential reactant for the Selective Catalytic Reduction (SCR) system's operation. The primary goal of the SCR system is to reduce harmful NOx emissions (nitrogen oxides emitted from engines), which pose risks to both human health and the environment. Selective catalytic reduction (SCR) is a technology used to clean exhaust gases after they pass through the engine. It involves injecting amounts of diesel exhaust fluid (DEF) into the exhaust system. This fluid then undergoes vaporization and decomposition resulting in the formation of ammonia and carbon dioxide.So mechanical joints at the DEF Dosing unit must be reliable such that it does not allow any exhaust gases leak out to the environment before passing through SCR. To prevent exhaust gases from leaking it is necessary to maintain gasket pressure more than exhaust gas pressure. FEA analysis iscarried out with different bolt preload values and with different geometric configurations. Compressive gasket pressure at the gasket is compared with the exhaust gas pressure value.

2. Literature Review

Mihaela Paunescu [2] experimentally investigated the gaskets durability under cyclic internal pressure application. The study is carried out on number of gaskets which differs in thickness and width. From this study it is revealed that the influence of the gasket thickness on flanged joint sealing is smaller than the influence of gasket width. P.C.B. Luyt et al. [3] investigated the effect of creep on sealing performance of the gasket joint using FEA and viscoelastic material model in ANSYS. It is observed that the number of bolt tightening increments and the time between the bolt tightening increments play a significant role.Using FEA using nonlinear unloading & loading characteristics of the gasket, N. Nelson & N. Prasad [4] examined the sealing behaviour of dual gasket flange joints.In order to maintain the dual gasket joint's leak-tightness, a bolt preloaded for the minimal compressive stress needed on gaskets is suggested using an empirical relation. The impact of gasket contact stresses on sealing effectiveness at bolted flange couplings was examined by M Krishna et al. [7].Experiments are used to obtain the nonlinear characteristics of the gasket in room temp. This study presents the effects of varying gasket substances and bolt counts on gasket stress on contact & rotation of flange.

FE Analysis

Geometric Details: DEF dosing system is configured such that there should be no exhaust gas leakage. The assembly has three gasket connections. MICA gasket at bottom side of the dozer comes in contact withexhaust gases directly. MICA gasket has very good resistance to the corrosion which would cause due to exhaust gases. Graphite gasket is used as second stage sealing. The DEF Dosing system is as showninfigure 1.

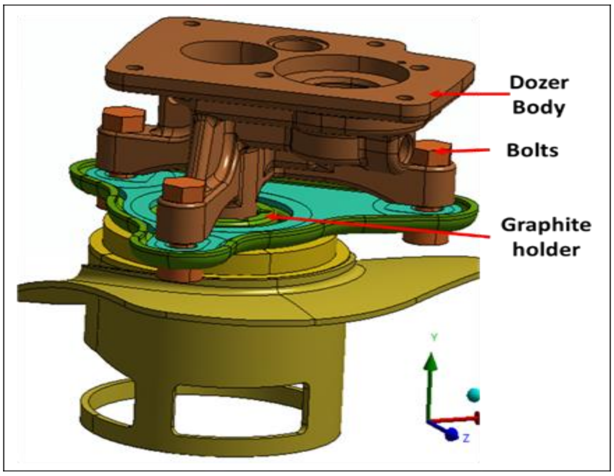

Figure 1 Geometric Details of DEF Dozing System

Material Properties: Structural steel material is assigned for Dozer body. Multilinear kinematic hardening material model as shown in figure 2 is used for retainer plate and for graphite gasket holder where plastic deformation may beoccur at high pretension in the bolts. True stress- strain curve is used for this purpose.

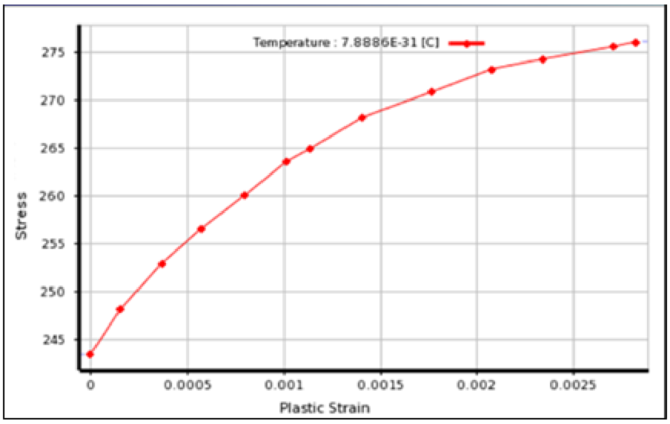

Figure 2 Multilinear Kinematic Hardening

Gasket bodies are modeled using GASKET material model available in ANSYS. In this material model LD curve of different gasket bodies can be given as a material behavior. The LD curve is determined experimentally for MICA as well as Graphite gasket.

Meshing: For the purpose of analysis 3-D FEA model is created. FEA software ANSYS Workbench 17.1 and 3D hex mesh is used to create model.

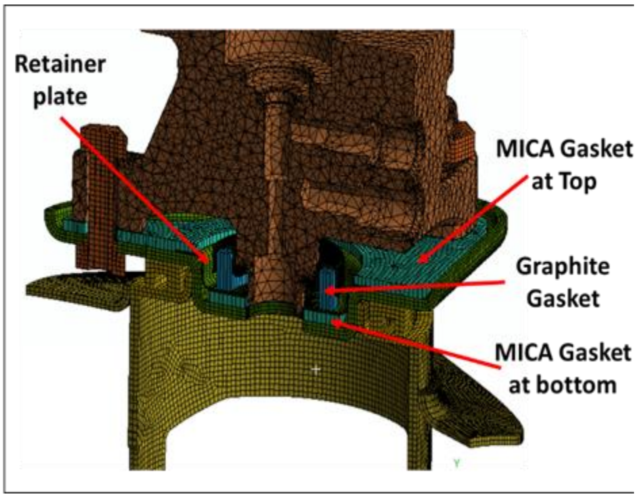

Figure 3 Mesh of the Assembly

All parts of the assembly except dozer body are meshed with SOLID-185 element in ANSYS. Dozer body is meshed with SOLID-187 element as hex meshing of the cast part is difficult in ANSYS and also dozer body is not a point of interest of this work. Bolts are also modeled with SOLID-185 element. Pretension element PRETS179 is used to apply pretension force.

Gasket material requires special meshing method. It is mandatory in ANSYS to do a sweep mesh for gasket material. And also it is required to have only one element division along the thickness direction of a gasket. Gaskets are meshed with 3D, 8 node gasket element (INTER195) available in ANSYS. Total node count in the FEA model is 201294. Analysis time with Intel's is 7, 8 core processor with 64 Gb RAM is 14Hours and 39 Minutes for one analysis.

Loading Conditions: Supporting plate of a DEF dosing system is fixed in all directions. Then Pretension is applied atthe each bolt. Analysis is carried out for three bolt pretension values.

i. Minimum pretension (6500N)
ii. Nominal Pretension (9000N)
iii. Maximum pretension (11500N)

Also, analysis is carried out for three different geometric configurations for each pretension value. So, total 9 runs are performed.

Three different geometric configurations are shown in figure 4:

a) 1.85mm gap between Dozer body and MICA Gasket at top – This configuration ensures maximum pretension load will be transferred to Graphite and MICA gasket at bottom before Dozer body comes in contact with MICA gasket at top. It creates maximum pressure at the MICA gasket at bottom and at Graphite gasket as desired. But, this may also cause plastic deformation in the graphite holding plate as well as retainer plate.
b) 0.15mm gap between Dozer body and MICA Gasket at top - This configuration ensures only 0.15mm initial displacement of the dozer body before dozer body comes in contact with MICA Gasket at top. It limits the force transferred to the Graphite gasket and MICA Gasket at bottom. It will cause no plastic deformation in the assembly but it may not be able to create required pressure

at the gasket which may results in leakage.

c) 1mm gap between Dozer body and MICA Gasket at top - This configuration ensures sufficient load transfer to graphite gasket that will prevent leakage and also will not cause any plastic deformation in the assembly.

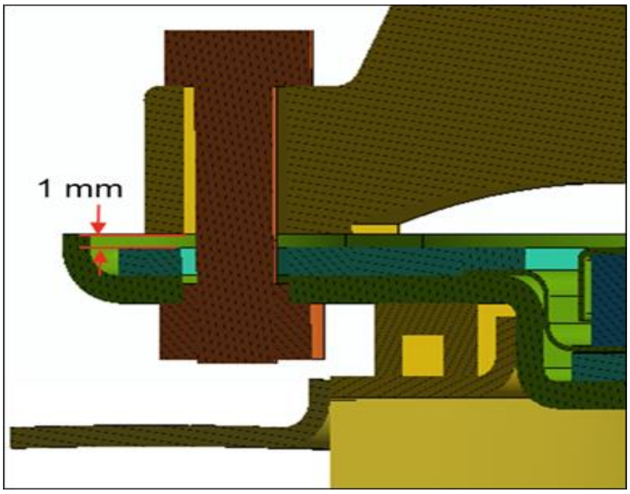

Figure 4 Different Geometric Configurations

Convergence: The simulation for dozer assembly is non-linear analysis. The kind of non-linearity included in the analysis is material non linearity, geometric nonlinearity as well as contact non linearity.

Material Nonlinearity: Dozer assembly has three gaskets to make leak-proof assembly. Gasket material has highly nonlinear behavior to the applied loading conditions. For every load increment stiffness of the gasket body changes and it shows nonlinear compression. The Load-Deflection curve is generated for the each gasket material experimentally and given as input material property. Another material nonlinearity in the assembly is yielding of the retainer plate and graphite holder plate. The yielding behavior is modeled using multi-linear kinematic hardening material model available in ANSYS.

Geometric nonlinearity: As gaskets are relatively soft materials, they get compressed easily. This will create high strain in the gasket material body.

Contact Nonlinearity: Surface interaction between gasket body and mating metal body is modeled using frictional contact.

Initially analysis is getting un-converged due to high deformation of the MICA gasket at the contact with Dozer body legs. There is high compression below dozer body legs and remaining surface of the gasket body is not loaded at all. This is causing element distortion and un-convergence of the simulation. This difficulty is resolved by adding a small shell element layer (0.1mm thick) at the free surface of the Gasket body. This restricts the elements at the free surface of the gasket from distortion (Hourglass effect). The size of theshell elements should be such, too thick elements may add stiffness at the gasket material whereas too thin element layer may not be able to restrict element distortion which will results in un-convergence of the simulation.

Results and Discussion

As motive of the analysis is to evaluate sealing performance of the gasket joint, gasket pressure is taken as a primary result output. Gasket pressure at the MICA gasket and Graphite gasket is checked after every loading condition. Maximum value of the gasket pressure is better from sealing performance point of view of gasket joints. But as higher pressure, may cause yielding of the other materials and sometimes crushing of the gasket body. Thus, plastic strain in the individual parts, maximum gasket pressure and Maximum gasket closure are also checked.

Pass-Fail Criteria:

- Minimum gasket pressure required should be above 1 MPa to prevent leakage of the exhaust gas.
- Ideally, there should no yielding of the material. But small percentage of yielding is considered. This yielding is occurred due to stress singularities at the sharp corner of the part.
- 80% of the gasket closure to its initial thickness is considered as crushing of the gasket. MICA Gasket has thickness of 2 mm so 1.8 mm or above closure of the MICA gasket is considered as crushing of MICA gasket. Graphite gasket is 6.6mm thick, so 5.3 mm and above closure of the graphite gasket is considered as crushing of graphite gasket.

Table 1 shows minimum gasket pressure around circumference of the gasket body. Table 2 shows Maximum equivalent plastic strain in the different parts. Table3 and 4 shows maximum pressure and maximum closure of the gasket respectively. The green color shows configurations which do meet the acceptance criteria whereas red color shows a value which fails to meet the criteria. Result plots are shown as follows:

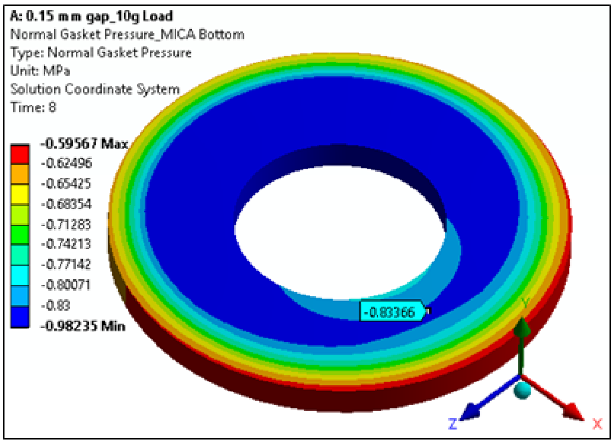

Figure 5Minimum Gasket Pressure for MICA Gasket at Bottom

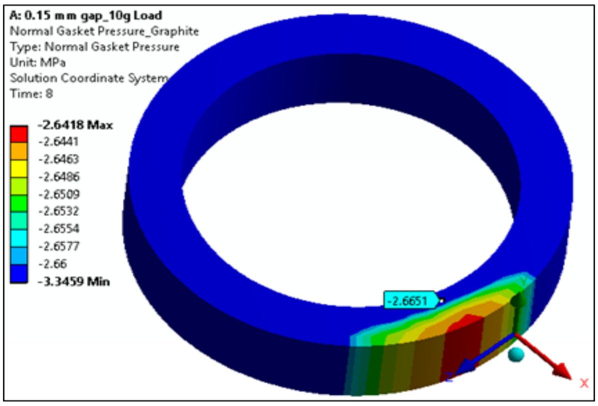

Figure 6 Minimum Gasket Pressure for Graphite gasket

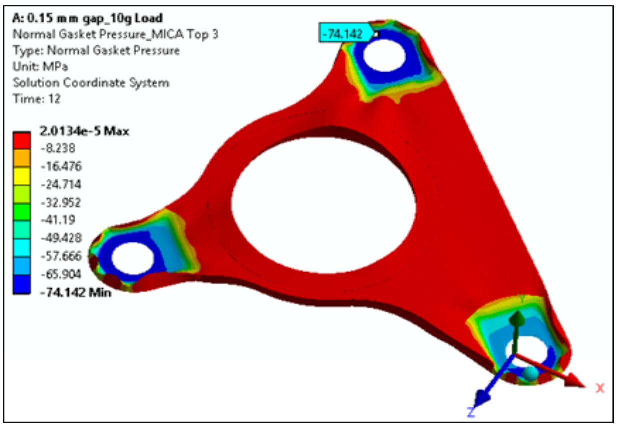

Figure 7 Maximum Gasket Pressure for MICA gasket at Top

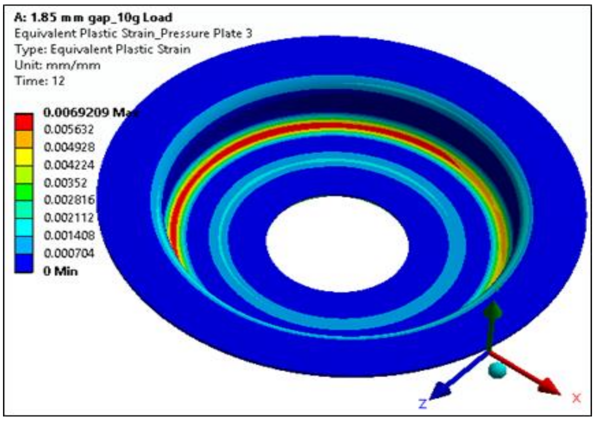

Figure 8 Plastic Strain at Retainer Plate

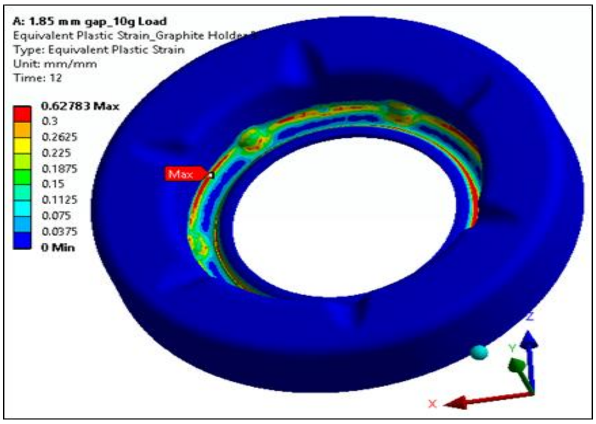

Figure 9 Plastic Strain at Graphite Holder

Table 1 Minimum Normal Compressive Pressure (MPa)

(Around Gasket Circumference)

Minimum Normal Compressive Pressure (MPa)							
Loading condition		0.15 mm gap		1 mm gap		1.85 mm gap	
		MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Bottom)	Graphite Gasket
Bolt Pretension	6500 N	0.83	2.66	2.34	7.6	2.55	7.3
	9000 N	1.37	4.61	2.43	7.9	4.58	7.1
	11500 N	2.05	6.75	2.5	7.8	5.87	6.7

Table 2: Maximum Equivalent Plastic Strain (% mm/mm)

Maximum Equivalent Plastic Strain (% mm/mm)							
Loading condition		0.15 mm gap		1 mm gap		1.85 mm gap	
		Retainer Plate	Graphite Holder	Retainer Plate	Graphite Holder	Retainer Plate	Graphite Holder
Bolt Pretension	6500 N	0	0.1251	0.210	15.042	0.33	56.8
	9000 N	0.071	0.879	0.236	33.212	0.55	62
	11500 N	0.217	7.39	0.444	43.84	0.69	62.7

Table 3 Maximum Normal Compressive Pressure (MPa)

Maximum Normal Compressive Pressure (MPa)										
Loading condition		0.15 mm gap			1 mm gap			1.85 mm gap		
		MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)	MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)	MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)
Bolt Pretension	6500 N	0.98	3.34	43.62	2.38	7.873	42.129	2.92	9.54	41.87
	9000 N	1.67	5.94	58.31	2.478	8.265	57.398	6.44	8.26	56.72
	11500 N	2.32	7.72	74.14	4.041	8.242	73.917	9.18	8.43	72.99

Table 4: Maximum Normal Closure (mm)

Maximum Normal Closure (mm)										
Loading condition		0.15 mm gap			1 mm gap			1.85 mm gap		
		MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)	MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)	MICA Gasket (Bottom)	Graphite Gasket	MICA Gasket (Top)
Bolt Pretension	6500 N	0.043	1.04	1.33	0.143	1.19	1.28	0.176	1.234	1.27
	9000 N	0.1	1.13	1.8	0.149	1.20	1.77	0.299	1.24	1.75
	11500 N	0.139	1.189	2.307	0.223	1.20	2.29	0.38	1.239	2.27

Experimental Analysis

LD Curve evaluation

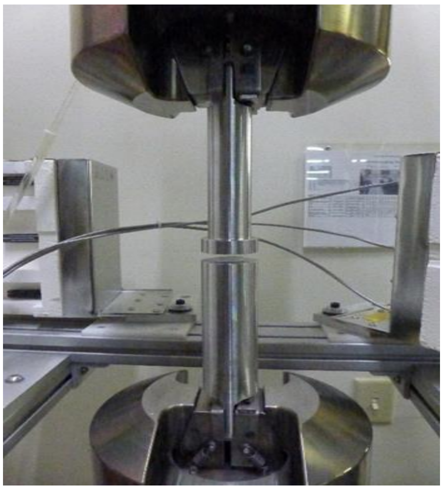

Figure 10 Experimental Setup

LD Curve for MICA Gasket and Graphite gasket is determined experimentally. Gasket material is placed between fixture bodies. Experimental setup is as shown in Figure 13.

Force is applied and removed repeatedly. Load is increased with every load step. Gasket material is compress on application of load and is retrieve on removal of the load. The path followed by Gasket material is not same in loading and unloading conditions. Gasket’s deflection is plotted against load applied. Each gasket material has its unique load deflection behavior.LD curve forGraphite gasket is as shown in figure 11 and LD curveforMICA gasket is as shown in figure 12.

These LD Curve are used during FEA Analysis

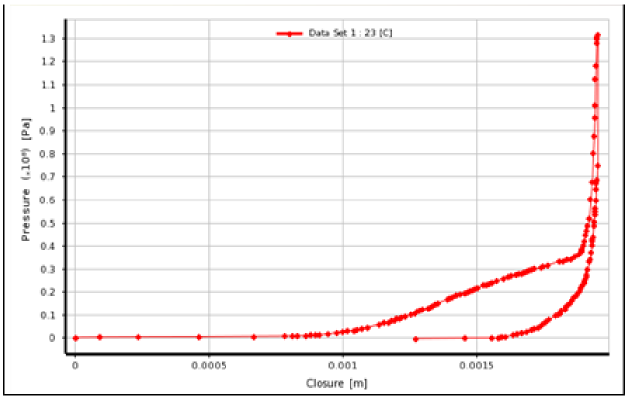

Figure 11 Graphite Gasket-LD Curve

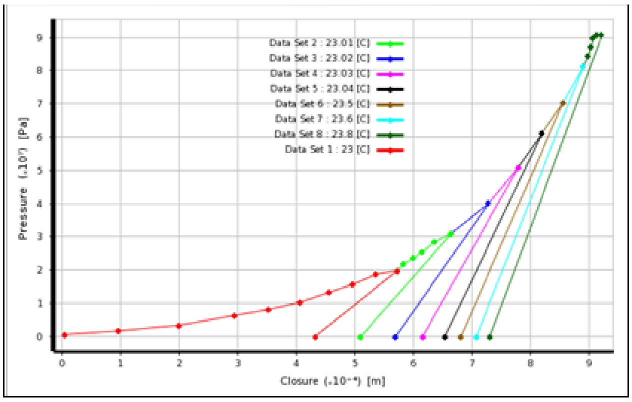

Figure 12 MICA Gasket-LD Curve

Conclusion

1. In case of 0.15 mm gap between dozer body and MICA gasket, Maximum load is transferring to MICA gasket at top and load transfer to the MICA gasket at bottom and graphite gasket is limited. Thus at minimum pretension condition of 6500N, pressure at MICA gasket at bottom is only 0.83 MPa. It is less than 1 MPa and thus fails to meet the acceptance criteria.

2. In 0.15 mm gap configuration, maximum load is being transferred to MICA gasket at top. High load on gasket causes crushing of the gasket at higher pretension value of 11500 N.

3. As load transferred to the MICA and Graphite gasket is limited, plastic strain in retainer plate and graphite holding plate is less than plastic strain in 1 mm and 1.85 mm gap configuration case.

4. At higher geometric gap configurations, gasket pressure at MICA and Graphite gasket is much high than required 1 MPa. It is desired from leakproof design point of view. But at the same time, plastic deformation in retainer plate and graphite holding plate is much higher. There may be chances of fracture of the material.

5. From all results it is clear that 0.15mm gap with nominal pretension of 9000 N is best possible solution within experimental range. The Minimum gasket pressure is 1.37 MPa, which is more than 1 MPa. Plastic strain observed is less than 1% and also no gasket crushing is observed.

Future Scope

Experimental study will be carried out on the DEF Dosing system to validate results obtained from FEM results.

References

[1] Lamins, Gasket Handbook A Technical Guide to Gasketing and Bolted Joints, pp. 3 - 111.

[2] MihaelaPaunescu, Experimental research regarding gaskets durability, International journalof fatigue, 2005

[3] P.C.B. Luyt, N.J. Theron, F. Pietra, "Non-linear FE modelling and analysis of the effect ofgasket creep-relaxation on circular bolted flange connections", International journal ofpressure vessels and piping, 2017.

[4] N. Rino Nelson a, N. Siva Prasad, "Sealing behaviour of twin gasketed flange joints", International journal of pressure vessels and piping, 2016.

[5] M. Abid, D.H. Nash, "Structural strength Gasketedvs non-gasketed flange joint under bolt upand operating condition", International journal of solids and structures, 2016.

[6] G. Mathan, N. Siva Prasad, "Study of dynamic response of piping system with gasketedflanged joints using FEA", International journal of pressure vessels and piping, 2012.

[7] M. Murali Krishna, M.S. "Shunmugam, N. Siva Prasad, A study on the sealing performanceof bolted flange joints with gaskets using FEA", International journal of pressure vessels andpiping, 2007.

[8] Haruyama S., Nurhadiyanto D., Choiron M.A., Kaminishi K., "Influence of surface roughness on leakage of new metal gasket", International Journal of Pressure Vessels and Piping, 111-112, 2013, p. 146-154.

[9] Nelson N.R., Prasad N.S., "Sealing behavior of twin gasketed flange joints", International Journal of Pressure Vessels and Piping, 138, 2016, p. 45-50.

[10] AS Chaudhary et. al. "Experimental investigation of Gerber frames subjected to elastic lateral torsional buckling", Australian Journal of Mechanical Engineering, 2022

[11] AS Chaudhary et. al. "Pre-buckling structural analysis of thin z-section under uplift loading", Journal of Pharmaceutical Negative Results, 2932-2943, 2023

[12] Beghini M., Bertini L., Santus C., Guglielmo A., Mariotti G., "Partially open crack model for leakage pressure analysis of bolted metal-to-metal flange", Engineering Fracture Mechanics, 144, 2015, p. 16–31

[13] Nechacke A., Bouzid A.–H., "On the use of plate theory to evaluate the load relaxation in bolted flanged joints subjected to creep", International Journal of Pressure Vessels and Piping, 85, 2008, p. 486-497.

[14] Igarashi S., Wakiyama N., Inoue K., Matsumoto T., Murase Y., "Limit design of high strength bolted tube flange joint, Part 1 and 2, Journal of Structural and Construction Engineering Transactions of AIJJapan, Department of Architecture reports", Osaka University, August 1985.

[15] G. Mathan, N. Siva Prasad, "Studies on Gasketed Flange Joints under Bending with Anisotropic Hill Plasticity Model for Gasket", International Journal of Pressure Vessels and Piping, 88 (2011) 495-500

[16] T. Sawa, Higurashi N and Akagawa H, "A stress analysis of pipe flange connections", Journal of pressure vessel technology, vol.113, pp. 497-503, (1991).

[17] Ma K, Zhang Y, Zhang L, et al. "Behavior of bolted joints with metal-to-metal contact type gaskets under bolting-up and loading conditions. ProcIMechE, Part E: J Process Mechanical Engineering 2014, pp. 1–8.

[18] Abid M, Iqbal M, Ullah B. "Comparative thermal stress analysis of gasketed and non-gasketed flange joints for safe operating condition". Proc IMechE, Part E: J Process Mechanical Engineering 2009; 233: 167–178.

[19] Khan KA, Abid M, Chattha JA. "Gasketed bolted flange joint's relaxation behaviour under different bolt up strategy". Proc IMechE, Part E: J Process Mechanical Engineering 2009; 223: 259–263.

[20] Boiler and pressure vessel code. Section II-D. New York, NY: American Society of Mechanical Engineers, 2004.

[21] Takaki T, Satou K, Yamanaka Y, et al. "Effect of flange rotation on the sealing performance of pipe flange connections". In: ASME Conference proceedings: Analysis of bolted joints 2004; 478: 121–128.

[22] M. Couchaux, M. Hjiaj et.al "Bolted circular flange connections under static bending moment and axial force", Journal of Constructional Steel Research, Volume 157, June 2019, Pages 314-336

[23] Y. Q. Wang, L.Zong, Y.J. Shi, "Bending behavior and design model of bolted flange-plate connection", Journal of Constructional Steel Research, Volume 84, May 2013, Pages 1-16

[24] Charkha, P.G., Jaju, S.B., "Analysis & optimization of connecting rod", *2nd International Conference on Emerging*

Trends in Engineering and Technology, ICETET 2009, pp.86, 2009.

[25] Jaju, S.B., Charkha, P.G., Kale, M., “Gas metal arc welding process parameter optimization for AA7075 T6”, Journal of Physics: Conference Series 1913 (1), 2021.

[26] N. P. Sherje, Ashish M. Umbarkar, Sameer A. Agrawal Prashant P. Kharche,Dharmesh Dhabliya, “Machinability study and optimization of CNC drilling process parameters for HSLA steel with coated and uncoated drill bit”, Materials Today: Proceedings(Elsevier) https://doi.org/10.1016/j.matpr. 2020. 12.1070