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Research Article

Methodology for selection of optimum interference fit for enhancing performance of external gear pumps

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Abstract

External gear pumps are the heart of mobile hydraulic equipment in the mining sectors where it requires precise control of work attachment functions, lubrication of transmissions and oil supply to steering control units. The external gear pumps encounter many tribological phenomena such as lubrication and wear of gear teeth, an inner profile of casing, wear plates, and press fitting of journal bearings. The major challenge involved during the design phase is the optimum selection of required interference dimensions between the shaft plain bushings and its housings such as bracket and covers. Though the analytical calculations provide some rough initial sizes, it is a time consuming and tedious process when it comes to different material combinations, non-uniform and unsymmetrical sections of brackets and housings. Also, it is difficult to include the effect of thermal variations and different surface finish conditions of mating surfaces in analytical calculations. Optimum interference dimensions are essential to avoid premature failure of the Pumps due to dislodging of the bushings. In the current study, the required initial interference fit dimensions are computed based on an analytical method for different materials combinations. Further, the effect of the surface finish of mating surfaces and thermal expansion of materials are studied using KISSsoft simulation. The validation of the same has been carried out using an experimental set up with different material and assembly conditions as a comparative study to find the optimum dimensions.

Keywords: *Gear Pump, Joint Interference fit, Plain Bushing, Dislodging, KISSsoft.*

1. Introduction

External Gear pumps are the positive displacement pumps which find its usage in almost all the hydraulic applications. viz., mining equipment, food processing industries, petrochemical industries, chemical industries, aerospace applications, agricultural machines etc., where it is required to pump the fluids from one place to another place efficiently with high pressure. In Mining applications particularly in mobile hydraulic machines like Dozers, Excavators, Dumpers and graders gear pumps are used to generate flow for operating the work attachments, operation of planetary transmissions by engaging and disengaging the clutches, lubrication and cooling of transmission gears and clutches, operation of steering control units etc. Efficient functioning of external gear pumps for the expected life involves proper design and selection of materials for its components such as brackets, gear casing, cover, thrust plates, bearings and sealing arrangements.

Tribology factors such as wear of gear tooth, an inner surface of the gear case, optimum shaft clearance and fitting dimensions of journal bearing, selection of wear plate materials etc., play a vital role in the reliability and satisfactory working of the external gear pumps. Plain bushings are the sliding contact bearings which are used to support the rotating shaft of driving and driven gears on both sides and to reduce the friction and wear. These bushings are press-fitted inside the bore of bracket and Cover. When the pump delivers high pressure oil, the bearings will be subject to very high radial loads which affect the volumetric efficiency of gear pumps.

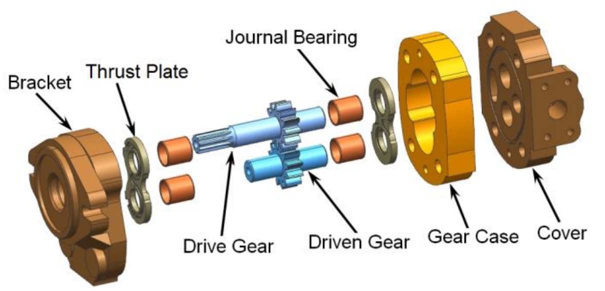

Fig.1 Main Components of External Gear Pump

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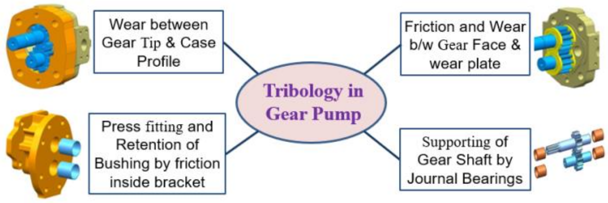

Fig.2 Tribology in External Gear Pump

Proper installation of the plain bushings inside the bracket and cover will help to assure that maximum performance and life of pump will be obtained. The certain magnitude of interference should be ensured to avoid sliding of the bearing inside the housing. However, too high interference will lead to more contact stress, reduction in bearing inner diameter, which will lead to a reduction in bearing clearance and further interference with the rotating shaft. Also, the improper assembly may damage bearing liners, cause excessive loading and may lead to bush dislodging from the bracket and reduce life. At present a large number of research papers are focussing on gear pump design parameters (E.A.P Egpe, 2013), general plain bushing design, journal lubrication, bearing materials wear rate and so on, and only few research papers focussing on interference fit of plain bushings.

A predictive tool for lubrication of dynamically loaded bearings confirmed that significant elastic deflection of bearings and housings and deterioration of the operating condition of the bearings (H. Xu *et al*). Efficiency and durability of the gear pump depend on proper consideration of tribological phenomena in the design process (Bishop. R. J *et al*). There has been a long-standing demand for understanding of the working mechanism and behaviour of journal bearings in the type of gear pumps. Recently, authors investigated the hydrodynamic lubrication of the journal bearing used in a gear pump application (Xu, H *et al*, 2001). The performances of the fit connection depend commonly on material, structure, interference/shrink range, finishing, etc. The work (J.F. Fontaine *et al*) simulated the optimal topography of contact surfaces in an interference fit for contact pressure and reducing edge effect while the surface form defects also considered. Later, it is found that form defects of fit surfaces have little effect on assembly strength of interference fit by studying numerically (H. Boutoutaou *et al*, 2011). The finite element simulation can be an effective tool for analysing fit connection (I. Sogalad *et al*, 2006). The roughness and the radial interference have an essential influence on the contact strength and friction coefficient and further torque capacity of shrink-fit assembly between cylinders which has been proved by experiments (Mascle C *et al*, 2017). However, for the external pump assemblies with different bracket materials, the mathematical relationship between radial interference and pump load, Press-in and Press-out forces and influence of the thermal expansion of housing bore and bushing material has not given directly.

In this article, the analytical methodology to arrive at a required interference fit dimensions between the housing bore of the bracket/cover and bushing surface with different materials of the bracket is carried out. Also, the impact of different surface roughness values and pump operating temperature in maintaining the effective interference fit is simulated using software tool KISSsoft. Further an experimental study conducted for making comparative study and validation of analytical and software analysis. The results are used to find the optimum interference fit dimensions for the bracket and bushing assemblies used in external gear pumps.

2. The analytical method for selection of interference fit

The idealized assembly diagram of bracket/cover and plain bushing used in external gear pump assembly considered for the analytical study of the interference fit is as shown in Fig.3. The housing and bushing dimensions are indicated by d_o for housing outer diameter, d_f for diameter at the contact surface and d_i for bushing bore diameter. Analytical method governs the selection of mean interference and tolerances for bushing outside diameters and housing bore diameters.

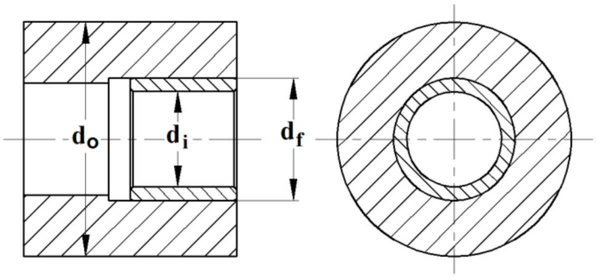

Fig.3 Configuration of bracket and bushing assembly

It is necessary to consider the following points for selecting the interference for an application: for the minimum required interference keep in mind that, the interference is reduced by radial loads, reduced by differences between bushing temp and ambient temperature and also by variation of fitting surfaces. For selecting maximum interference, one should remember that too tight interference will result in excessive contact stress and result in squeezing of bushing and interference between shaft and bushing affecting the journal clearance and hence seizure of the pump.

There are two basic approaches for the selection of interference fit. In the first approach, the required interference shall be calculated by establishing the class of fit (Table.1) and tolerances (Table.2). Once the interference and tolerances are calculated, the next step is to arrive at the maximum and minimum diameters for the housing and bushing from the nominal diameters. The pressing-in F and pull out forces for varying interference limits and different housing materials are calculated based on the mathematical relation, as mentioned in the equation (1) as given below.

$$F = 2\pi\mu r f \, l p f \tag{1}$$

where,
μ - coefficient of friction between mating surfaces
l - Length of interference surfaces.

Table.1 Classes of fit (Steven R.Schmid *et al*, 2014)

Class	Type	Application
1 to 4	Clearance	Where clearance is required between rotating parts
5 (Wringing)	Interference	Where light tapping with a hammer is required to assemble
6 (Tight)	Interference	In semi-permanent assemblies suitable for drive or shrink fits on light sections
7 (Medium)	Interference	Suitable for press fits on medium parts like motor parts, automotive wheels etc
8 (Shrink)	Interference	Where considerable bonding between surfaces is required

Table.2 Recommended tolerance in mm for fit class (Steven R.Schmid *et al*, 2014)

Class	Interference	Housing tolerance	Bearing tolerance
5	0.000	$0.0052d^{(1/3)}$	$0.0035d^{(1/3)}$
6	0.00025d	$0.0052d^{(1/3)}$	$0.0052d^{(1/3)}$
7	0.0005d	$0.0052d^{(1/3)}$	$0.0052d^{(1/3)}$
8	0.0010d	$0.0052d^{(1/3)}$	$0.0052d^{(1/3)}$

The second one is based on limiting the circumferential stress and radial deflection of mating parts at contact surface. The interference pressure (P_f) is caused by interference between the bushing and housing, and this pressure increases the radius of the hole and decreases the radius of the bushing, which results in a specific interference fit. The method to calculate the interference pressure (P_f) and required radial interference (δ_r) between housing and bushing is given by equations (2) & (3) (Steven R.Schmid *et al*, 2014).

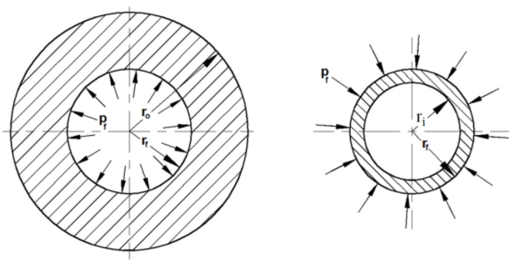

Fig.4 Contact pressure at bore and bushing OD of interference

$$p_f = \left(\frac{\sigma_{max}(r_o{}^2 - r_f{}^2)}{(r_o{}^2 + r_f{}^2)} \quad \text{(or)} \quad \frac{\sigma_{max}(r_f{}^2 - ri^2)}{(r_f{}^2 + r_i{}^2)}\right) \tag{2}$$

$$\delta_r = r_f p_f \left(\frac{(r_o{}^2 + r_f{}^2)}{E_h(r_o{}^2 - r_f{}^2)} + \frac{\nu_h}{E_h} + \frac{(r_f{}^2 + r_i{}^2)}{E_b(r_f{}^2 - r_i{}^2)} - \frac{V_b}{E_b}\right) \tag{3}$$

Where,
r_o - the outer radius of housing,
r_f - the radius at the contact surface,
r_i - the inner radius of the bushing,
σ_c - allowable circumferential stress at the contact area,
E_h, E_b -elastic modulus of housing and bearing material,
ν_h, ν_b - poisons ratio of housing and bearing material.

The increase in temperature of the pumping oil during the continuous running of the equipment will be transferred to the bushing and housing material. It will result in thermal expansion, and significant change in the effective interference which can be analyzed by the mathematical equation (4) shall be considered for calculation of required interference which will otherwise lead to dislodging of the bushing from the housing.

$$\delta_{rt} = \alpha_t \, \Delta T \, r_f \tag{4}$$

where,
δ_{rt} - radial displacement due to temperature rise.
α_t - coefficient of linear thermal expansion.
ΔT – the difference between room temperature and operating temperature.

3. KISSsoft Simulation

Though the analytical method is used for calculation of required initial interference values, it is considered to be reasonable only when there is a smaller number of contacting pairs and effects of thermal expansion; surface conditions are ignored. Also, when the choices of combining materials and iterations of mating dimensions considering tolerance range and surface conditions to arrive at optimum fit are more, it becomes a tedious and time-consuming process. KISSsoft is one of the software tools recently finding its vast usage in the design process of machine elements and mechanical systems. The Interference fit design module includes an extensive library of mating materials to choose. The GUI interface of the KISSsoft cylindrical interference fit module is as shown in Fig.5. It facilitates to simulate the interference fit design with various mating conditions like calculating the contact pressure and stresses on parts for the entire tolerance range in a single run compared to the analytical method. The effect of operating temperature, the surface conditions, loads in circumferential and axial directions and the load with bending moment and radial forces on the mating pairs can be studied with higher accuracy in lesser time. The application of this tool can examine the influence of centrifugal forces on the joint and the maximum torque for non-slipping fit. The press-on and press-out forces, the safety of the interference fit against sliding and the protection of shaft and hub material against fracture and yield point can be calculated more efficiently.

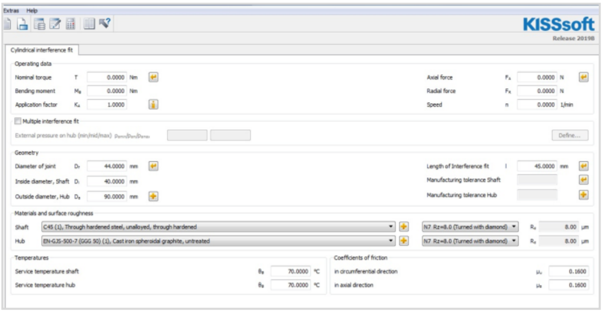

Fig.5 GUI Interface of KISSsoft Interference Analysis.

The present analysis is carried out for two different combinations of pump bracket and bushing materials. The bracket materials considered are spheroidal Graphite Iron (SG500-7) and Aluminium. The hot rolled steel plate material is used for journal bushing. The analysis carried out for the radial interference of 25, 30, 35 and 45, 50, 55 microns between bracket and bushing surface with the operating temperature of 50 deg.C, 60 deg.C and 70 deg.C. The different surface roughness condition of the mating bracket and bushing surfaces considered for analysis are 0.4 Ra, 0.8 Ra, 1.6 Ra, 2.4Ra and 3.2 Ra. The above combination of materials, radial interference, operating temperature and surface roughness values made it to a total of 150 iterations in the KISSsoft analysis. The bracket and bushing assembly that are press fitted together are shown in Fig.6

Table.3 Nominal dimensions of Interference Joint

Parameter	Values
Nominal Diameter at Contact surface	44 mm
Bushing ID or Shaft diameter	40 mm
Outer diameter of Housing (Bracket/Cover)	90 mm
Length of Joint	45 mm

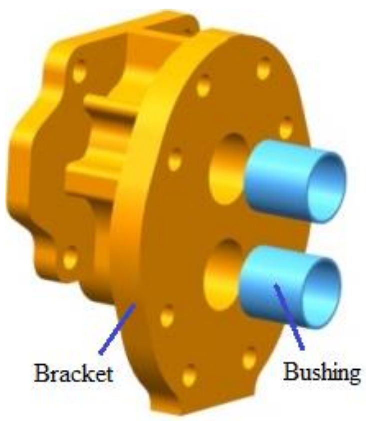

Fig.6 Bracket and Bushing Assembly.

The nominal interference joint dimensions of the bracket and bushing for the 160 Cc/Rev capacity external gear pump, which is considered for the present analysis are tabulated, as mentioned in Table.3. These dimensions are arrived based on the basic component sizing of the external gear pumps for a particular capacity at rated pressure and speed.

The resulting press-on and press-out forces, radial displacement of bracket and bushing are used for the comparative study with the results obtained by experimental validation so that the optimum required interference can be arrived for the joint. The amount of embedding resulting from the rubbing of metal to metal surfaces due to surface undulations is the notable results from the above analysis.

4. Experimental set-up

Totally six number of brackets, three for Aluminium and three for SG500-7 materials are manufactured (Fig. 7) to study, compare and validate the analysis results. Three brackets of Aluminium material are machined with the bore dimension of 39.990 mm (radial interference 45 microns), 39.980 mm (radial interference 50 microns) and 39.970 mm (radial interference 50 microns. Another three brackets of SG500-7 material are machined with the bore dimension of 44.010 mm (radial interference 35 microns), 44.020 mm (radial interference of 30 microns) and 44.030 mm (radial interference of 25 microns). The surface finish of 0.4 to 0.8 Ra maintained during machining for both the brackets. The journal bushing used for assembly of all the above four brackets is the hot rolled steel bushing with an outer diameter of 44.080mm. The force required for pressing the bushing inside the bracket and the necessary force to press out the bushing completely from the bracket are measured and recorded using the universal testing machine. The experimental set-up used for the study consists of a press with force measurement and the controller unit, as shown in (Fig. 8 & 9).

Fig. 7 Bracket in Machined condition and Bushing

Fig.8. Components of Experimental Set-up

Fig.9 Image of pressing of Bushing inside Bracket

5. Results and Discussion

The Ideal interference values arrived based on the analytical method for both Aluminium and SG500-7 bracket with steel bushing are as shown below.

Table. 4 Analytical Interference values

	Aluminium Bracket	SG500-7 Bracket
Radial Interference as per Class of Fit	48	48
Radial Interference as per Analytical Calculation	45	27

The KISSsoft analysis started with the above initial values to identify the effective interference, also by considering the surface roughness conditions and thermal effects due to a rise in oil temperature during the running condition. Fig.10, and Fig.11 indicates the effect of contact surface embedding in the resultant active interference for the SG500-7 material and the Aluminium bracket material. As the surface roughness reduces, the effective interference starts diminishing due to the effect of increased surface embedding.

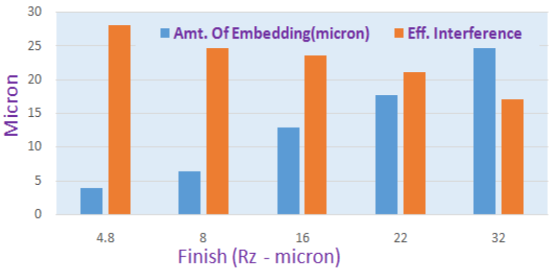

Fig.10 Amount of embedding and Effective interference Vs Surface Roughness for SG Iron Bracket

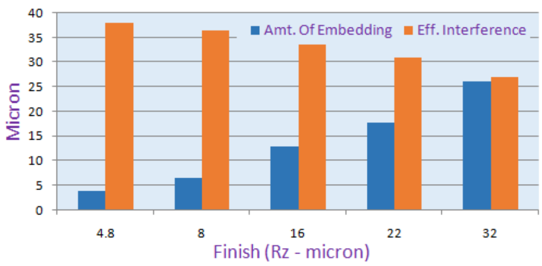

Fig.11 Amount of embedding and Effective Interference Vs Surface Roughness for Al-Bracket

Fig.12 & Fig.13 indicates the amount of force required to press in the bushing inside the SG500-7 and Aluminium bracket. The press-in force is increasing as the surface quality increases since the well finished surface will provide uniform distribution of contact pressure between mating surfaces. Also, the amount of force increases as the radial interference increases.

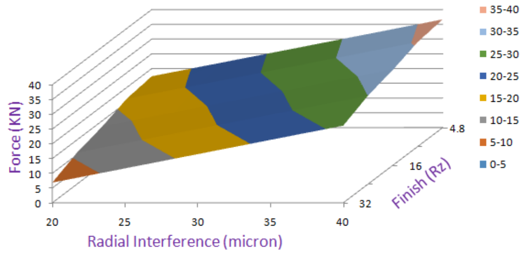

Fig.12 Pressing-on Force Vs Radial Interference Vs Surface Roughness for SG500-7 Bracket

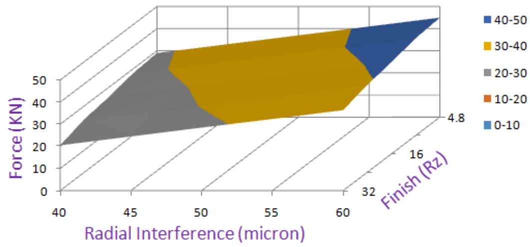

Fig.13 Pressing-on Force Vs Radial Interference Vs Surface Roughness for Al-bracket.

Fig.14 & Fig.15 indicates the amount of force needed to press out the bushing completely from the SG500-7 and Aluminium bracket. The amount of force required for press out the bushing from the bracket is increasing as the surface quality increases. Also, the amount of force increases as the radial interference increases.

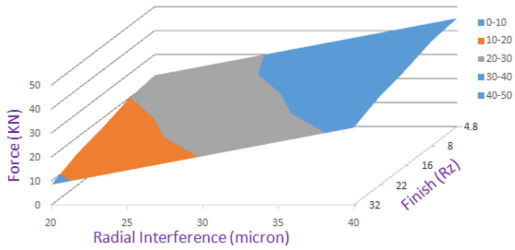

Fig.14 Pressing-out Force Vs Radial Interference Vs Surface Roughness for SG500-7-Bracket

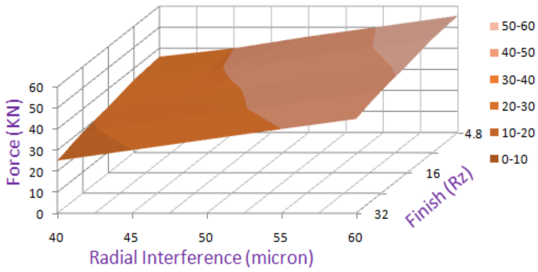

Fig.15 Pressing-out Force Vs Radial Interference Vs Surface Roughness for Al- bracket.

Table. 5 Comparison of Press-on Force by Analytical Vs KISSsoft Vs Experimental Method.

Bracket Material	Radial Interfer-ence	Analytical	KISS-soft	Experim-ental	% Deviation compared with Experimental Data	
					Analytical	KISSsoft
SG Iron	25	17.5	15.54	14.8	15%	4.7
	30	20.9	19.40	18.7	10.5%	3.6
	35	24.5	23.20	22.75	7.1%	1.9%
Al-Alloy	45	26.4	25.2	25.7	2.6%	2%
	50	28.9	27.3	26.9	6.9%	1.5%
	55	31.8	30.2	29.6	7%	2%

The calculation of force required for press-in the bushing is being calculated by an analytical method and KISSsoft Analysis. The results are compared with the values obtained through the experimental study conducted for press-in the bushings for three varieties of SG500-7 bracket and three varieties of the Aluminium bracket. The comparative study carried out is tabulated in table.5 as well as represented graphically in Fig.16 and Fig.17. The study shows that the calculated press-in force values through KISSsoft analysis are well nearest (2% to 4.7% deviation) to the experimental study compared to the analytical calculation (2.6% to 15% deviation). This is because, the different influential factors such as effect of surface roughness, effect of embedding, reduction in effective interference due to thermal effects, etc., which are assumed or neglected in manual calculations are possible to be included in the KISSsoft analysis.

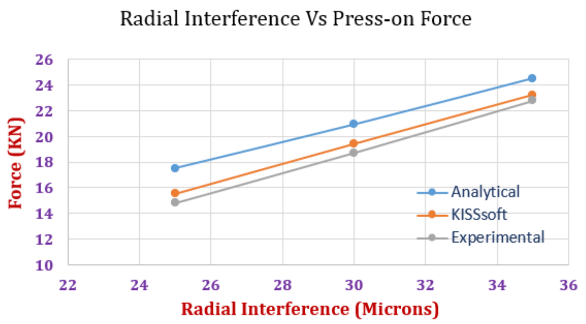

Fig.16 Radial Interference Vs Press-on Force comparison for SG500-7 bracket

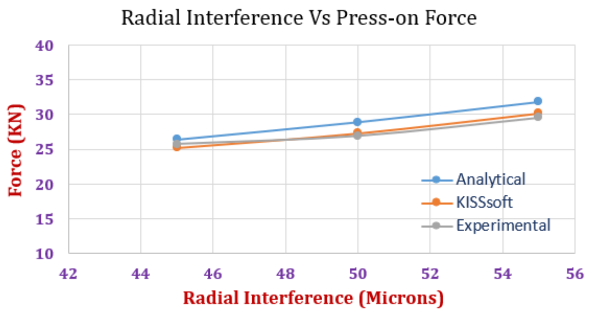

Fig.17 Radial Interference Vs Press-on Force comparison for Al- bracket

Fig. 18, & Fig.19 shows the comparison of press-in and press-out forces required with respect to the radial interference for the bushings with SG500-7 bracket and Aluminium bracket calculated by KISSsoft analysis. The press-out forces required are higher than the press-in forces for the same radial interference. This is one of the very important phenomena to retain the bushings in the housing for effective performance of the pump assembly.

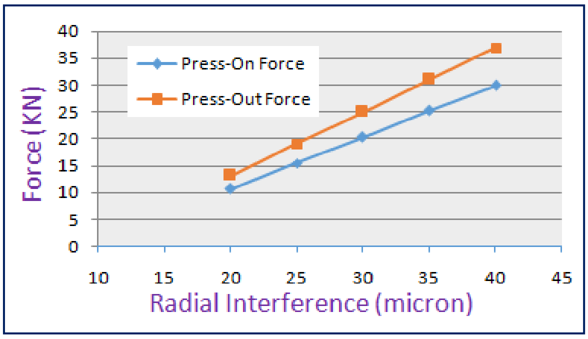

Fig.18 Radial Interference Vs Press-on & Press-out Force comparison for SG500-7 bracket

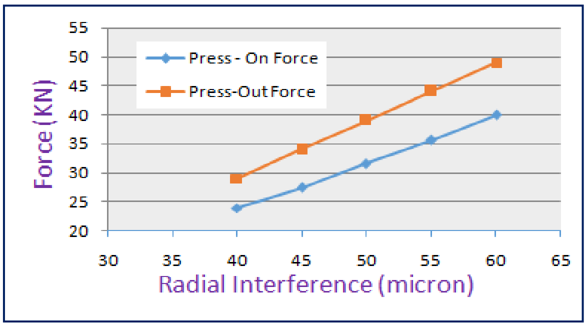

Fig.19 Radial Interference Vs Press-on & Press-out Force comparison for Al- bracket.

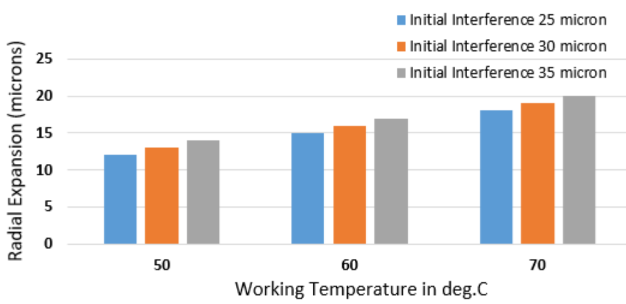

Fig.20 Effect of thermal expansion Vs working temperature Vs radial interference (SG500-7)

Fig.20 indicates the amount of thermal expansion with respect various operating temperatures and for different initial radial interference which is arrived using the KISSsoft simulation. As the working temperature increases the amount of thermal expansion in the housing bore increases which will have detrimental effect on the effective interference. It is needless to mention that the above thermal expansion factor should be considered in the design stage to avoid failure of pumps due to bushing dislodging and to enhance the pump performance.

Table. 5 Comparison of existing and modified design with SG500-7 Bracket Material

	Al / SG 500-7 Existing Design	SG 500-7 Modified Design
Radial Interference (µm)	45 - 55	25 - 35
Radial disp. @ Housing ID(µm)	+4.84	+4.84
Radial disp. @ Bushing OD (µm)	-39	-18
Radial disp. @ Bushing ID (µm)	**-42**	**-12**
Shaft OD (mm)	39.970 ~ 39.980	39.970 ~ 39.980
Fitting ID Required	40.000 ~ 40.060	40.000 ~ 40.060
Bearing Radial Clearance Required	50 ~ 90 /	50 ~ 90 /
Bearing Radial Clearance available	**13~48**	**45~70**

The effective interference required for the external gear pump bracket and bushing assembly are analyzed with different radial interference values with different surface conditions and operating temperature. The study shows that the effective interference required for SG500-7 bracket is lesser than the effective interference required for Aluminium bracket. As the Young's modulus and the thermal expansion co-efficient of Aluminium material are low compared to SG500-7 material, the radial expansion due to contact pressure will be more in Aluminium bracket and hence more joint interference is required for Aluminium bracket material. Based on the above analysis the effective radial interference is reduced to 25~30 microns from 45~55 microns for SG500-7 bracket when compared to Aluminium bracket. The resulting radial displacement and effective bearing clearances are tabulated in table.5. The modified effective interference value of 30 microns resulted in the bearing clearance of 45 to 70 microns in-place of existing 13 to 48 microns which is needed to maintain the minimum bearing running clearance to avoid dislodging of the bushing and to enhance the pump performance.

Conclusion

The detailed study and analysis for selection of optimum interference between Journal Bearing (Steel plate) & its bracket housing (SG 500-7 Iron (or) Al-Alloy) carried out based on analytical method and KISSsoft with different radial interference value. The effect of different interference values on assembling, dis-mounting forces and radial displacement has been studied in detail using latest Computational tool KISSsoft. The effect of surface finish and consequential embedding between contact surfaces and resulting reduction in effective interference also studied in detail. The results from Analytical method and KISSsoft are validated by conducting experimental set-up, and the comparative study carried out for press-on/out forces shows that KISSsoft results are in good agreement (less than 4.7% variation) with the experimental results compared to analytical method. The above methodology in present study can be very effective method for designing of interference joints.

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