Study on Staking Tool Configuration for Mounting Spherical Bearing

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Abstract – *Staking is an assembly process for mounting spherical bearing, which provides a light weight reliable joint by means of lip plastic deformation. The Spherical bearing retention in a Plate or hardware may be accomplished by threaded bearing retainer, bolted retainer or groove stake method. In groove stake method, Plate has a small groove machined into each face, which leaves a lip on plate inner diameter corner. With the use of staking tool, these lips are swaged over the chamfered or curved edges of the bearing. In present investigation, required staking load is applied by torquing the fastener. If nut factor of fastener is known, required staking load can be applied in controlled manner by torquing the fastener. Present study also covers comparison of various configuration staking tools, its design including material selection, staking load calculation, FE analysis and experiment carried out to study tool effectiveness. The staking tool performance results are compared to finalize suitable staking tool for carrying out staking operation on aerospace hardware.*

Key words: Staking tool, spherical bearing retention, staking load by fastener, plate with groove, bending load, staking failure load, bearing installation etc.

1.INTRODUCTION

Installation and retention are important consideration for spherical bearing assembly on plate or hardware. Mostly, assembly consists of one malleable material part, which allows to use pneumatic, hydraulic or electromechanical press to crimp, stake, swage or clinch it to retain the other part. For added strength, the second part can include a ridge, chamfer, arc or other feature to retain the material that flows from the first part. The spherical bearing is widely used in aerospace field as a key flexible connection, which requires a light weight assembly process. A typical spherical bearing installation, which is staked into the plate, is shown in Fig 1.

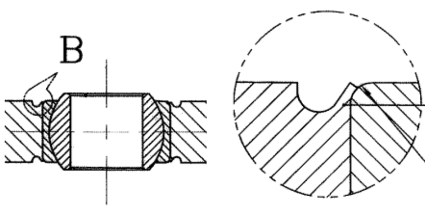

Fig - 1: Spherical bearing installation & retention on Plate

The precision assembly of spherical bearing is a typical case which has attracted great attention from researchers. Many studies have been conducted on part assembly with forming technology, Mori et al. (2013) brief about such metal joining process [1]. Roller swaging is a promising technology for assembly of spherical bearing. Qinglong Zhang (2016) did investigation for roller swaging process for self-lubricating spherical bearing assembly [2]. The analytical model of forming load based on process parameters was proposed, which shows good agreements with the results of experiments and 3D finite element model. Further investigation on housing chamfer parameters in roller swaging process was conducted [3]. The little chamfer height is beneficial to obtain a good joint condition with sufficient metal deformation. Liquid Propulsion System Centre uses spherical bearing stake assembly for actuator mounting support as shown in Fig- 2. Manual malleating of plate material was followed for bearing retention and there was no adequate test to assess the soundness of the stacking process. Subsequently based on this study staking tool was configured and acceptance load test were introduced.

Fig - 2*:* Actuator mounting interface

In staking operation, downward force is applied for forming retention points or surface. It is important to monitor or control every aspect of the operation, measuring both force & displacement to ensure that the right amount of force is applied in the right spots. Hence pneumatic, hydraulic or electromechanical presses are used. It involves rigorous experiments for finalizing staking press parameters, this needs time and cost. The design criteria of light weight aerospace supporting element calls for effective utilization of available space, which results complex geometry support element. In some cases, geometrical complexity makes staking process difficult. Staking tool for mounting spherical bearing using fastener provides easiness in staking process. This also allows in-situ staking of bearing. The staking tool configuration makes this process easy with good control in applied force. Staking force application is by torquing the fastener as shown in Fig-3. This staking method is already in practice for similar application. However, tool configuration and load application depends on plate material, bearing material and its retention configuration. Present study is done for malleable plate material AISI 316L with U groove configuration and spherical bearing with radius at the corner, bearing outer race material is 17-4PH.

The staking tool assembly configuration for staking top face is shown in Fig-3. With the knowledge of experimentally evaluated nut factor of fastener, the required staking force can be calculated as below

Staking force (F):

= Applied torque / (Nut factor x bolt dia.) (1)

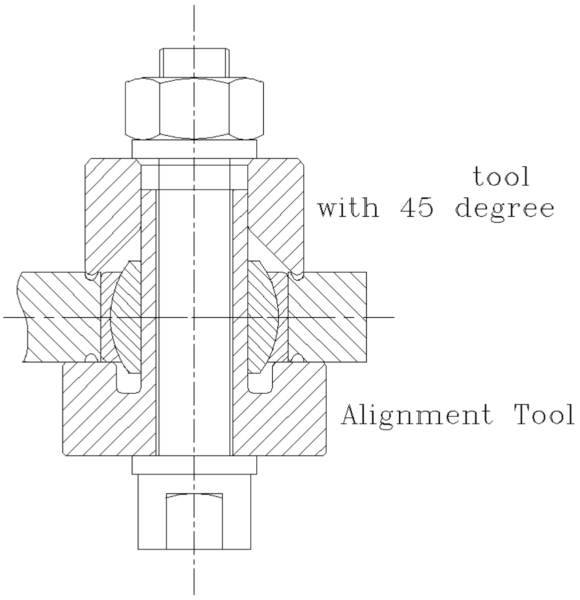

Fig - 3: Staking tool assembly detail for staking on top face

Many factors are influencing the torque-tension (force) relationship including material, size, plating, surface finish, thread lubricant, corrosion & wear of fasteners, nuts and washer. The nut factor conveniently summarizes all the variables that are known to influence the torque-tension relationship. It is an empirical value that linearly models the rate at which tension or force is developed within a fastener when torque is applied. Tension developed in the fastener during the torquing represents the applied staking force. By using precise torque wrench, required force can be applied in staking process. The configuration of staking tool makes controlled load application in required retention locations.

2. STAKING LOAD ESTIMATION

The bearing staking operation on plate can be assumed as a bending process. The staking force is applied to bend the lip and form the desire shape. In staking process, the required bend force is applied by staking tool as shown in Fig-3. The staking force consists of two elements, the bending moment due to bend force and additional force to overcome the contact surface friction. The staking force is influenced by parameters like lip thickness, tensile strength of plate material, strain hardening characteristic of plate material, staking tool contact surface geometry and plate geometrical parameters. The tool to plate contact is assumed as circular line, friction between contact surfaces is not considered.

A typical bearing assembly is considered for load estimation. The important geometrical parameters affecting staking process is shown in Fig-4. The bend or staking force can be expressed as (Forming process, 1997 by Kalpakjian for bend force estimation) [16].

$$F=KLSt^2/w \qquad (2)$$

Where,

F = Staking or bending force in N

K = 0.33, Section shown in figure 4 can be treated as a wiping die [15]

L =πD, Length of circular bend part in mm

t = Lip Thickness in mm

S = Ultimate tensile strength in N/mm²

w=0.3, Width between contact points in mm (Deformed lateral width of lip as shown in figure 4)

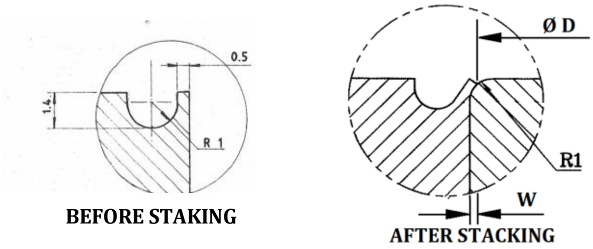

Fig - 4: Staking process for spherical bearing assembly

Tested mechanical property of AISI 316L is mentioned below.

Table 1: Tested Mechanical properties of AISI 316L

Mechanical properties (N/mm2)	
Yield strength	298
Ultimate strength	606

Calculated staking force (F): 15706 N

Hence it is required to apply force 15706 N(minimum) for the staking operation.

3. STAKING TOOL CONFIGURATIONS

The spherical bearing retention configuration and staking tool geometrical configurations are studied. Tool contact surface may have angle or radius (as shown in figure 5), geometrical parameter of different tools is judiciously chosen. The staking tool configuration permits proper guided assembly, staking load application at required location, and proper holding of the Plate without damaging the bottom groove with provision for fastener assembly.

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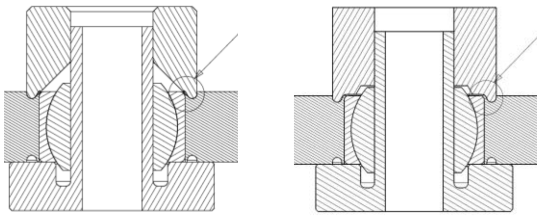


Fig-5: Staking Tools with radius and angle

Staking tool contact surface plays important role for proper hugging and retention of spherical bearing in plate. 2D axisymmetric finite element analysis is carried out using 'multi-linear kinematic hardening plasticity model' with tested strain data for plate material. The coefficient of friction 0.3 was assumed for staking tool/plate contact surfaces [14]. The analysis results are generated by giving downward motion to the staking tool. Downward motion of staking tool results in application of staking force and plate lip is getting deformed as shown in figure 6. It is expected that lip should bend and follow spherical bearing profile, this results reduction in lip diameter. Figure 7 shows, reduction in lip diameter and staking force with time for 45 tool, there is no much increase in staking force application up to point 'O' as the applied staking force is mostly utilized for bending the lip. It can also be inferred that tool displacement beyond 0.5 seconds (subsequent to lip bending) may cause load application to the plate material which results thinning. Hence 45° tool displacement is limited to 0.5 seconds for arriving the optimum staking load 14835 N.

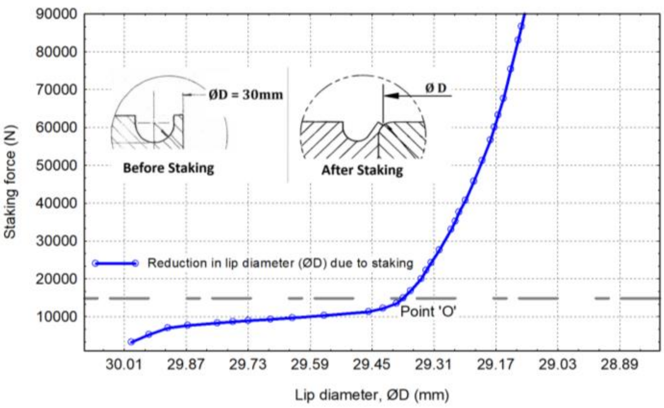


Fig-6: Reduction in lip diameter (ØD) during staking operation using 45° tool

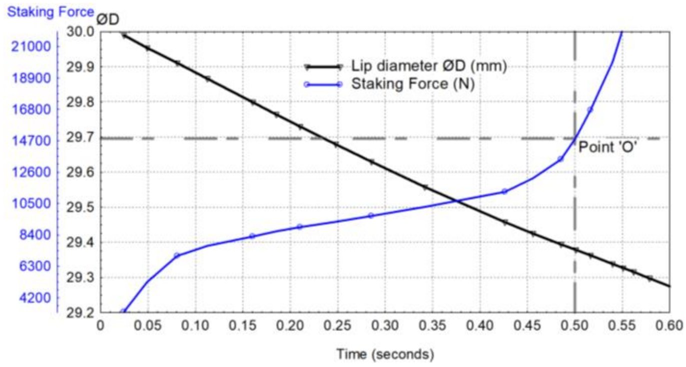


Fig-7: Lip diameter (ØD) & staking force variation with time for 45° tool

Further tool displacement or load application will cause unwanted additional load on lip and bearing which may affect the bearing performance and reduction in lip thickness. The deformed lip should follow spherical bearing outer race profile with greater reduction in lip diameter.

Similar analysis was carried out for different tool configurations and results are obtained. Lip deformation results for staking tools with angle 45°, radius R1.1, R1.44 and R2.5 are shown in Fig - 8. It can be observed that tool with angle 45° and R1.44 results are better. The analyzed staking load is less for R1.1 tool as the applied staking load is not properly utilized for lip bending due to selected tool configuration. Stacking load is varying for different staking tool configurations due to change in load application point.

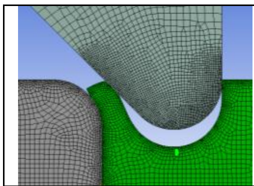
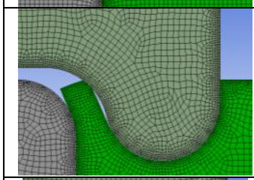
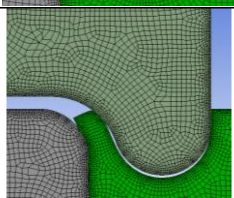
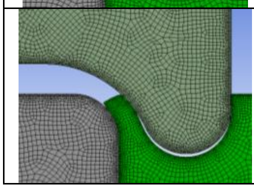
	• Tool with angle 45° • Achieved reduction in Plate lip diameter ØD: 0.62mm • Staking force=14835 N
	• Tool with R1.1 Fillet • Achieved reduction in Plate lip diameter ØD: 0.55 mm • Staking force=11969 N
	• Tool with R1.44 Fillet • Achieved reduction in Plate lip diameter ØD: 0.61 mm • Staking force=15435 N
	• Tool with R2.5 Fillet • Achieved reduction in Plate lip diameter ØD: 0.52 mm • Staking force=14305 N

Fig - 8: FE Results, Lip deformation profile for different types of Staking Tools

4. MATERIAL SELECTION AND FABRICATION OF STAKING TOOLS

The staking operation is to be done on AISI 316L plate. For effective staking process and long tool life, tool hardness should be more than the lip material to be deformed. The measured hardness of AISI316L is 25 HRC hence AISI 440C is selected for the realization of Staking tools. Hardness range of heat treated AISI 440C material is 56 to 63 HRC.

Different configurations of staking tool viz., 45°, R1.1, R1.4, R1.44 and R2.5 were realized. Fig. 9, 10 & 11 shows a sample of realised hardware and their cross sections for 45° and R1.4 tools along with the alignment tool. Plates as shown in fig12 were fabricated. This contains five holes with 10 U grooves for staking operation. Two sets of plate were realized to carry out the spherical bearing staking experiment.

***Fig-9**: Staking tool with angle 45°*

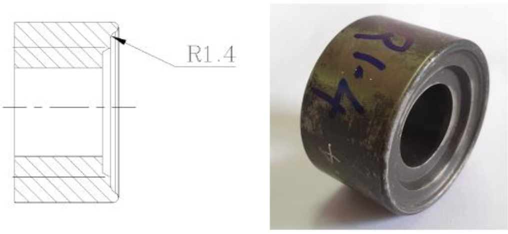


Fig-10: Staking tool with R1.4

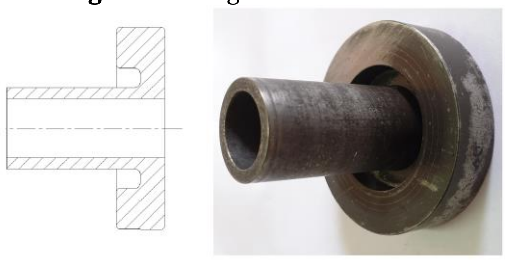


Fig-11: Alignment tool

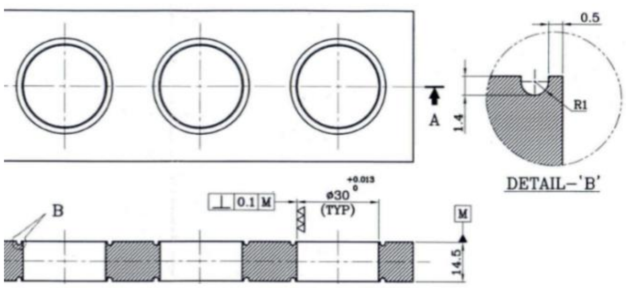


Fig-12: Plate for spherical bearing staking

5. EXPERIMENTS ON PLATE

Each hole & U-groove interfaces were marked and identified. Staking operation was carried out using single or multiple tools. A set of M12 fasteners (bolt, washer and nut) identified for the usage is shown in Fig-13 along with staking tools, plate-1&2 and spherical bearing. To quantify the applied force, nut factor was evaluated. The achieved average nut factor is 0.3 hence for applied torque 50, 70 and 90 Nm, the tension on fastener or staking force will be 13888.8 N, 19444.4 N and 25000 N respectively. The expected lip deformation is shown in Fig-14.

Fig-13: Staked interfaces, Plate, Staking Tools, Fastener set and Spherical bearing

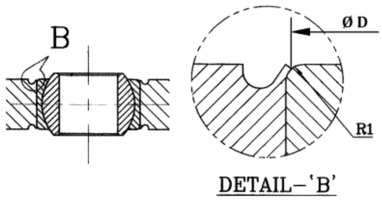


Fig-14: Diameter measurement after staking process

The staking operation is carried out using fabricated tools (i.e., 45°, R1.1, R1.4, R1.44 and R2.5), subsequent to staking process the deformed lip diameter (ØD) is measured as shown in Fig-14. The lip diameter is expected to reduce due to staking process. Hugging of lip to bearing corner radius can also be seen visually for any gap. No gap confirms proper hugging. The staked interfaces were visually inspected after the staking operation. Staking operation on plate 1 (hole 4 and 5) was carried out with different torque (with 45° tool) and reduction in lip diameter was measured. It can be inferred from chart 1 that reduction in lip diameter with incremental higher torque is insignificant after 70Nm. Hence considering the uncertainty in staking load application due fastener usage, torque application (minimum) ~70 Nm was chosen. This ensures that required stacking load is applied.

Effectiveness of staking process is verified by measuring the change in lip diameter by calculating the difference in lip diameter before and after the staking process (torque application) as mentioned in chart 1, 2, 3, 4, & 5. Greater reduction in staked diameter was observed for Conical 45°, R1.4 and R1.44 tools. Proper hugging of lip to the spherical bearing is also noticed.

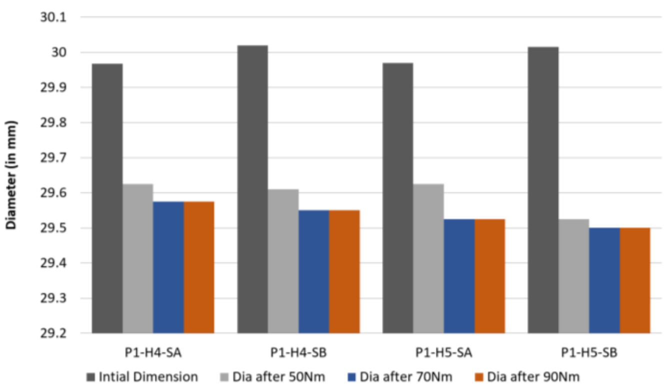


Chart - 1: Pre & post staking lip diameter of plate I with different torque with 45° tool
(P1-H4-SA means staking on plate 1, 4th hole and side A)

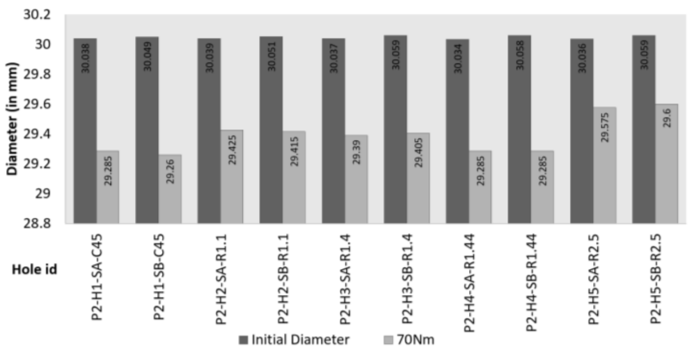


Chart - 2: Staking Experiment on Plate-1
(P2-H1-SA-45 means staking on plate 2, 1th hole, side A with 45° tool)

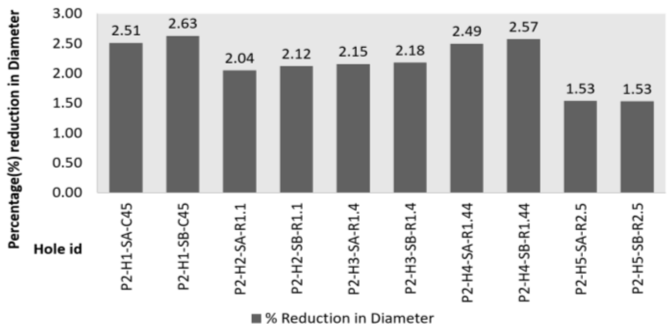


Chart - 3: Percentage Reduction in diameter for Plate-1

The combination of various staking tools is also attempted for the same interface as mentioned in chart 6. However, no significant further reduction in diameter is observed for the chosen tool combinations.

The plate thickness is also influencing the final staked diameter. This can be inferred from the Charts 1 & 3 and table 2, where staking operations of hole 1 for each Plate I & II were carried out using conical 45° tool and greater reduction in diameter is noticed for the Plate-I. Staked interfaces are shown in fig. 15 & 16 with its location marking for reference.

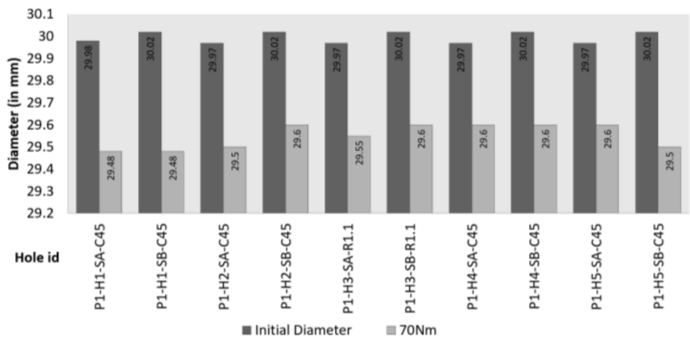


Chart - 4: Staking Experiment on Plate-2

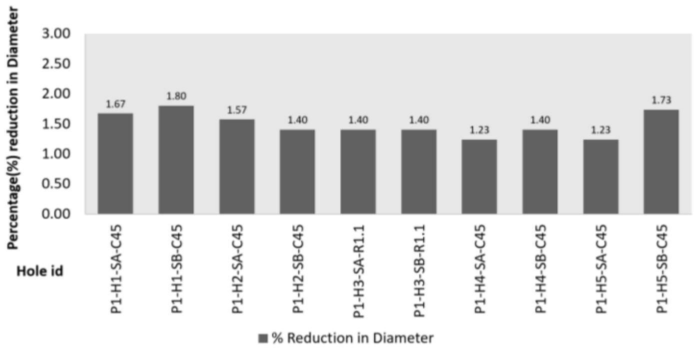


Chart - 5: Percentage Reduction in diameter for Plate-2

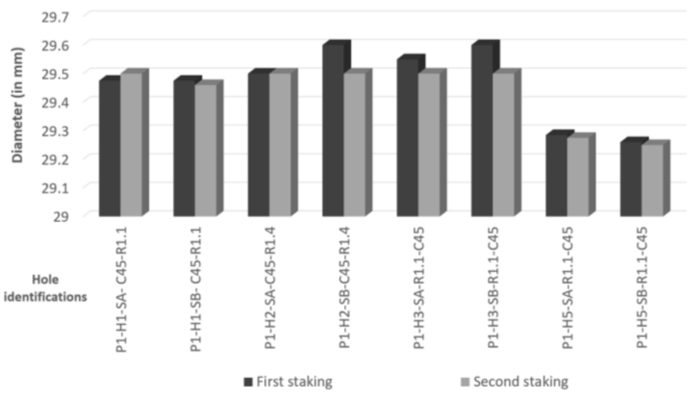


Chart - 6: Diameter with combination of staking tool for Plate-1.
(P1-H1-SA-45-R1.1 means staking on plate 1, 1th hole, side A staking with 45° tool followed by R1.1 tool)

Table 2: Staking Experiment on Plate-1 & 2

Plate no.	Specimen Thickness	Achieved reduction in diameter for Hole 1
Plate 1, Side-A	14.51 mm	0.7 mm
Plate 1, Side-B	14.51 mm	0.8 mm
Plate 2, Side-A	14.37 mm	0.5 mm
Plate 2, Side-B	14.37 mm	0.5 mm

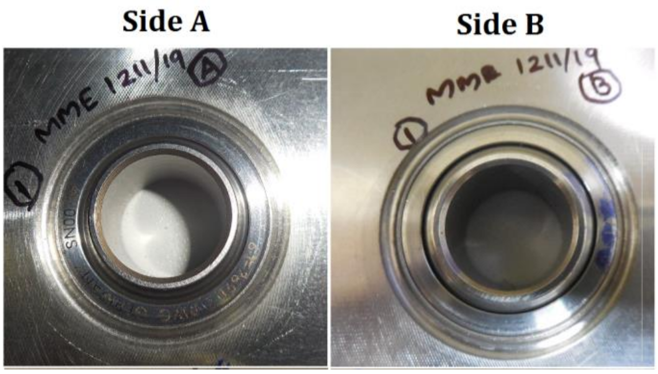


Fig - 15: Staking on Plate-2 hole-1, Id. No. MME 1211/19

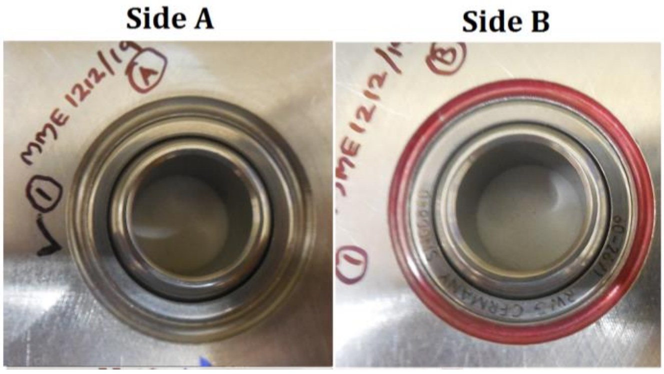


Fig - 16: Staking on Plate-1 hole-1, Id. No. MME 1212/19

6. HARDWARE REALIZED AT INDUSTRIES

The experiment results suggest that the staking operation with tools 45° and R1.44 are better compared to other considered tool configurations. Considering the fact of load application by conical surface, minor deviation in groove dimensions will also be taken care. Hence 45° tool is chosen for hardware realization in industries. Charts 7, 8 & 9 shows the details for hardware realized in three different industries. Variation is observed in staked diameter due to deviation in realized hardware's however it meets the requirement.

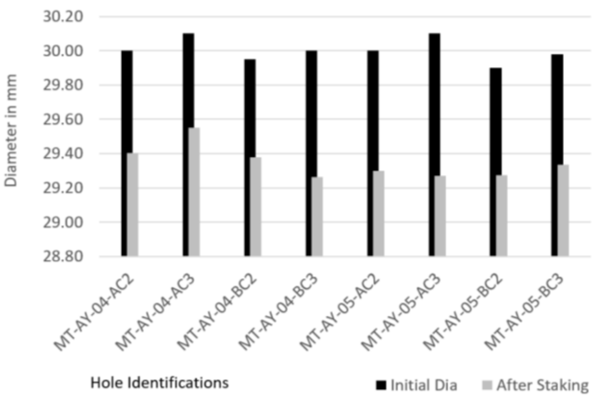


Chart - 7: Staking operation on hardware at Industry -1

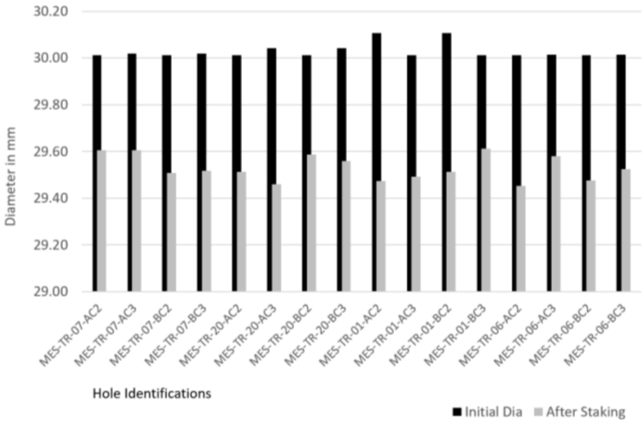


Chart - 8: Staking operation on hardware at Industry -2

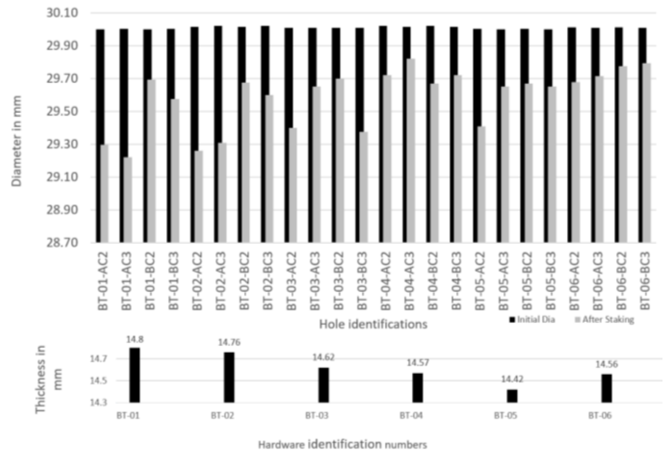


Chart - 9: Staking operation on hardware at Industry -3
(Bottom chart shows the plate thickness at bearing mounting locations)

It can be inferred from table 2 and chart 9 that the plate thickness plays a major role for the proper staking operation. If plate thickness is more, staking tool assembly configuration will make greater reduction in staked diameter for the one side, which is staked first. The staking operation is first done for BT-01 & BT-02 on side 'A' hence greater reduction in staked diameter is observed however same is not true for side B. The thickness in bearing mounting location on hardware BT-01 & 02 is slightly more as mentioned in chart 9. Hence plate thickness must be judiciously chosen considering the bearing outer race thickness.

7. LOAD TESTING OF STAKED INTERFACES

All the staked plate interfaces are acceptance load tested as shown in Fig-17, to verify its retention capacity for expected load in actuator mounting interface. The acceptance load test is successfully completed for all the staked interfaces.

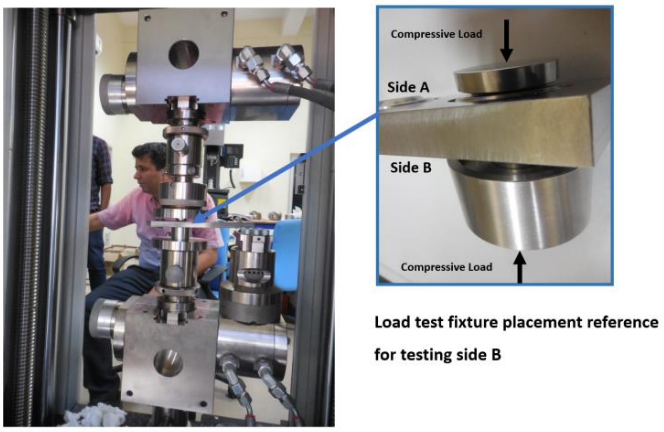


Fig - 17: Compression load test of staked interface

Subsequent to this all the staked interfaces were subjected to compression load test till failure. The compression load was applied at the rate of 1mm/min during the test. The obtained failure load is mentioned in Table- 3 and failed interfaces are shown in Fig-18. The tested minimum failure load is 5 kN.

Table 3*:* Failure load of stacked interfaces

-	Hole Id	Maximum compression load at failure (kN)	Utilized tool details
Plate-2	1A	6.974	Conical 45° followed by R 1.1
	1B	6.712	Conical 45° followed by R 1.1
	2A	Not recorded	Failure load could not be recorded, R 1.1
	2B	Not recorded	Failure load could not be recorded, R 1.1
	3A	7.018	R 1.4
	3B	6.340	R 1.4
	4A	6.969	R1.44
	4B	6.937	R1.44
	5A	5.353	R 2.5
	5B	5.047	R 2.5
Plate-1	1A	7.785	Conical 45° followed by R 1.1
	1B	7.044	Conical 45° followed by R 1.1
	2A	7.231	Conical 45° followed by R 1.4
	2B	7.269	Conical 45° followed by R 1.4
	3A	6.749	R 1.1 followed by Conical 45°
	3B	6.498	R 1.1 followed by Conical 45°
	4A	6.268	Conical 45°
	4B	6.097	Conical 45°
	5A	6.155	Conical 45°
	5B	6.194	Conical 45°

Fig-18: Load tested till failure

The staking failure load depends on hugging quality of lip to the bearing, lip thickness & height, mechanical property of plate material, friction between the plate and bearing material and type of fit resulting from hole inner diameter and bearing outer race diameter. Considering the variables influencing the failure load, it is difficult to interpret from Table- 3, However it is indicating that failure load is more for tools R1.44, R1.4 & 45°, resulting in improved joint with these tool combinations.

8. CONCLUSIONS

The failure observed in staked interface of actuator mounting was due to inadequate staking operation. Subsequently based on this experiment, staking tool and procedure was finalized. Quality check of staking process is also introduced by measuring the lip diameter before and after the staking process, visual verification of staked interfaces and acceptance load tests. The following points can be inferred from the experiment

- Staking of Spherical Bearing on plate is successfully demonstrated using fastener for load application using different configuration tools.
- This staking methodology can be easily adopted for complex shape plate, where roller swaging or other staking process is difficult to implement.
- The staking tools: Conical 45° and R1.44 are giving better reduction in staked diameter after staking operation however tool design may be further optimized by amending the tool geometry and experiments on a greater number of plates.
- This study is done for U groove configuration on plate and radius on bearing retention point, detailed study can be carried out for different groove configuration on plate and fillet or radius on bearing retention point.
- Combination of various tools for staking same interface was also attempted. However no significant improvement is observed in staked diameter.
- The thickness of plate plays major role for achieved staked diameter. Hence it must be controlled. However, required plate thickness depends on spherical bearing outer race thickness.

- The minimum estimated staking load is 15706 N, however considering the uncertainty in nut factor and nut factor variation due to repeated use of fasteners, 70 Nm torque is preferred to ensure that minimum staking force is applied during staking at the industry.

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