EXPERIMENTAL ANALYSIS OF COLD WORK IN AN OVERLAP JOINT OF ALUMINUM ALLOY FOR A WING-TO-WING ASSEMBLY

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Abstract. *Cold work is a method used to increase the fatigue life in aeronautical components by means of induced compressive residual stress. This is a result of strain hardening on the discontinuity area. Traditional cold work approaches are largely applied on aeronautical industry, but demand excessive time to be completed. Recent studies have shown that the cold work caused by the fastener riveting along with adequate drilling class might result in superior performance compared with the traditional cold work forms for structural joints. Therefore, this experiment was performed using several approaches: Finite Element Model of software programs CATIA® and ANSYS®, literature comparison and actual fatigue testing. The main objective is to prove that cold work created through interference fit on a special drilling class with Pull-Stem pins in an overlap joint – similar to a wing-to-wing assembly – could result in the expected fatigue life improvement, in comparison to the same joint with Hi-Lite pins. The main potential contribution relies on a faster manufacturing method that provides higher fatigue life to the component.*

Keywords: *cold work, drilling class, interference fit, fatigue life*

1. INTRODUCTION

Manufacturing processes in the aeronautical industry use riveted or bolted joints in large scale, which require the components to be drilled. This way, fastener holes are created which causes geometric discontinuities and local stress, or strain concentration during loading. According to Xavier, 2006, joints are the greater spot of stress, commonly responsible for structural element failure. Investigations showed that there were several accidents caused by fatigue failures initiating from fastened joints, such as the Aloha Airlines Flight 243 accident. According to statistics, fatigue fractures of fasten holes account for 50–90% of fractures of aging planes (Yucan, 2015).

One of the primary challenges in this scenario is to increase the residual compressive stress in order to improve the fatigue life. Nonetheless, this type of stress is proportional to the design properties of the drilled component. Due to main bearing structures size and cycling loads life, they present a great need for safety and fatigue strength, which makes the improvement more desirable.

Hence, it is important to develop new methods able to achieve the desirable fatigue strength to the components. The interference fit, which is a consequence of forced installation of a fastener that has a shank purposely larger than the hole it is intended for, increases significantly the fatigue resistance of assembled structures subject to alternative loading (LISI, 2018). This method is being used, since the fatigue life can be increased, as discussed, through the compressive stress gain. Moreover, the cold work or cold expansion is another process that can, in most cases, result in at least 3:1 fatigue life improvement (Fatigue Technology, 2018). In this case, an oversize tapered mandrel pre-fitted with a lubricated split sleeve is applied through the holes drilled and then removed, in order to create a residual stress zone, as shown in Figure 1.
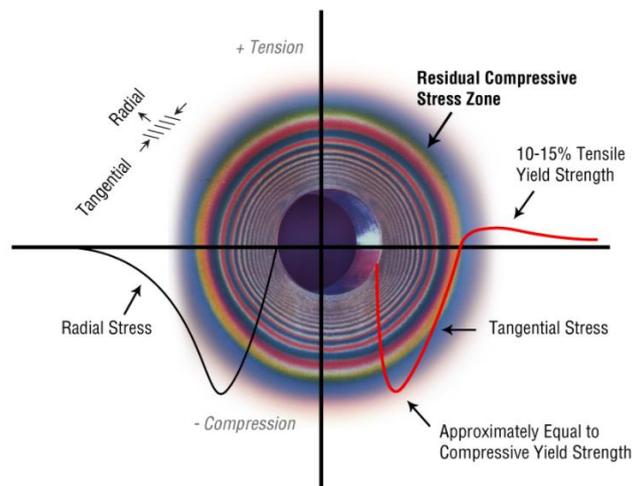
Figure 1. Stress zones around a drilled hole after cold expansion process. Source: Fatigue Technology, 2018.

The cold word presented itself as a potential solution to increase the residual stresses on typical mechanical fastened joints, increasing the component fatigue life and preventing early crack initiation, and then extending the life span of aircrafts (PAPANIKOS, 1998). Despite the known cold work techniques, another option that could be applied is the increasing of the interference fit level between pins and holes pairs, in substitution to the mandrel process. In this particular case, both techniques of cold work and interference fit are mixed, within steps of usual cold work and characteristics of high interference fit process. This way, cold work is being studied as a method that can be created while the fasteners are being installed, due to its own riveting process. In this case, there is no removal of the pins, leading to the execution of the first part of the traditional cold expansion process, which creates more desirable compressive stress on the hole and, due to the lack of mandrel use, is capable of reducing the production time by eight minutes per hole (EMBRAER, 2018).

The main purpose of this work was to analyze how the cold work through the drilling process affects the fatigue life of an overlap joint made of 7050 aluminum alloy in the T7451 condition with four titanium alloy pins as fasteners. Moreover, this work aimed at providing a summary of the comparison between the pertinent data available previously and the data obtained through current tests. The coupling of simulated data and results of actual fatigue tests prompt an alternative to the drilling and riveting processes typically adopted until now.

2. METHODOLOGY

Research was developed through five main steps: literature analysis and comparison, Finite Element Model simulation, specimen construction and a fatigue test.

The first one corresponded to the analysis of all data available regarding cold work, its uses and further comparison. This demonstrates the data simulated and obtained from the tests. Moreover, two studies of cases evolving aircraft accidents were done.

The second part of the research dealt with modeling and simulation through Finite Element Model of CATIA®. Different loads were applied on the model in order to evaluate the more accurate one to rupture the specimens within 100,000 cycles. Further, similar simulation was run through ANSYS®, looking forward more detailed stresses for both specimens type, accordingly to the standard diameter of each. This way, the radial and tangential stresses were acquired. In this part all the pertinent information respecting the parameters and constrains was append.

The third part was the construction of specimens. A number of 34 specimens were built, half containing HST12BJ-12-9 pins made of Titanium alloy 6Al-4V, and the other half, HSL1416NKA12-9 pins of the same material. During this phase, all holes and pins were measured using a Coolant Proof Micrometer Series 293-with Dust/Water Protection Conforming to IP65 Level, Mitutoyo, to assure compliance with the manufacturing standard used by Embraer. The holes had two measurements done for maximum and minimum diameter and all pins had their diameter shank measured three times in different heights. For the HSL holes, the tolerance varied from 9.427 to 9.467 mm, while for HST holes it varied from 9.462 to 9.487 mm. Furthermore, the pins tolerance for both cases varied from 9.4869 to 9.5123 mm. Finally, the nominal diameter of pins and holes was 9.5 mm.

The final step consisted of the actual fatigue tests. They were performed in laboratory running the cycles within the same load applied to all specimens. This included adjusting the machine requirements, such as frequency, amplitude, load and grip pressure applied to keep the specimens still during test. In order to set the adequate test conditions, one specimen of each model was preliminary used and the initial load was guessed regarding the CATIA® simulation.

3. RESULTS

The first approach of the work resulted in encountering the failure modes capable of happening due to the joint type, main parameters to be considered during the analysis and test conditions to guide the fatigue cycling of specimens. The S-N curves considered in this phase were largely applied during the next one, while making the comparison between literature and simulation, aiming for more assertive results.

For the second part of the work, the desirable load to cause the specimens to rupture at 100,000 cycles was calculated using data tracked as 45 Ksi, or 3.10e+8 N/m². The results were compiled into tables, containing the main information and complimentary drawings of the model created. Figure 2 shows the mesh parameters, load simulations, specimen drawings and results after simulation.
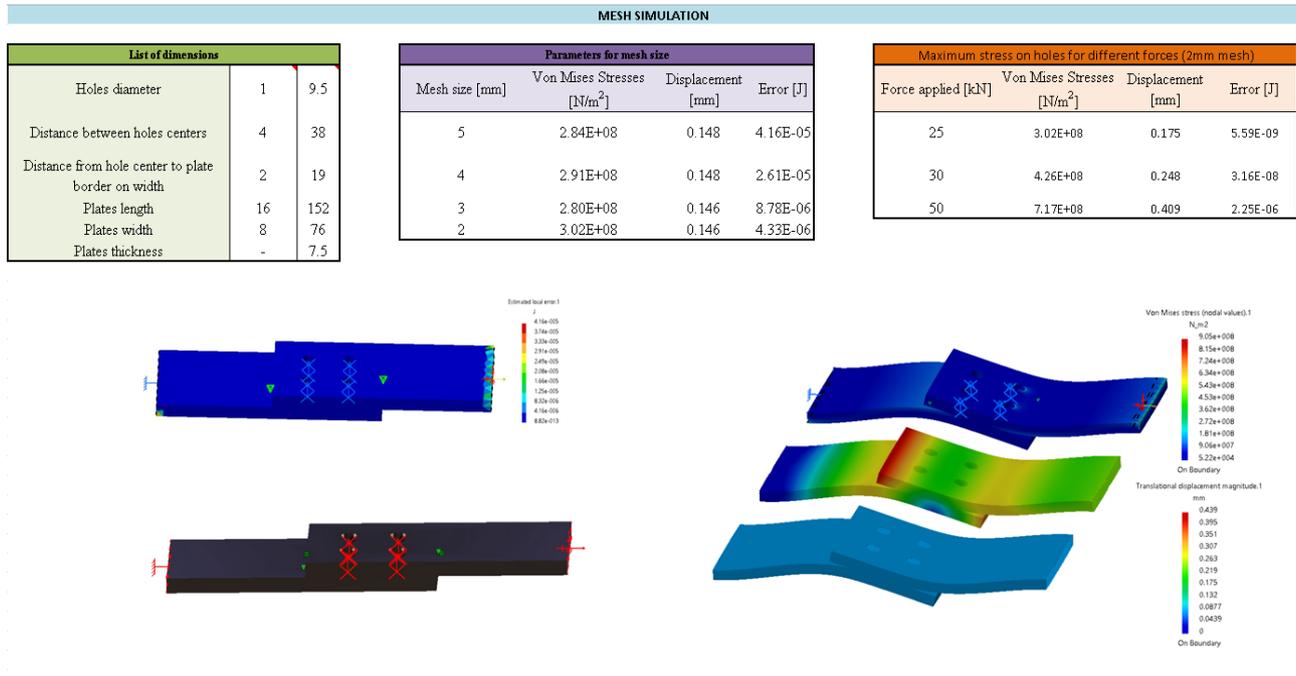
MESH SIMULATION

List of dimensions		
Holes diameter	1	9.5
Distance between holes centers	4	38
Distance from hole center to plate border on width	2	19
Plates length	16	152
Plates width	8	76
Plates thickness	-	7.5

Parameters for mesh size			
Mesh size [mm]	Von Mises Stresses [N/m²]	Displacement [mm]	Error [J]
5	2.84E+08	0.148	4.16E-05
4	2.91E+08	0.148	2.61E-05
3	2.80E+08	0.146	8.78E-06
2	3.02E+08	0.146	4.33E-06

Maximum stress on holes for different forces (2mm mesh)			
Force applied [kN]	Von Mises Stresses [N/m²]	Displacement [mm]	Error [J]
25	3.02E+08	0.175	5.59E-09
30	4.26E+08	0.248	3.16E-08
50	7.17E+08	0.409	2.25E-06

Figure 2. Simulation data on CATIA®. Source: Author.

After the simulation, the next step was to compare the concentration factor K_T, obtained from simulation, to the calculated through NIU, 1995, as shown on Figure 3 as 4.99.
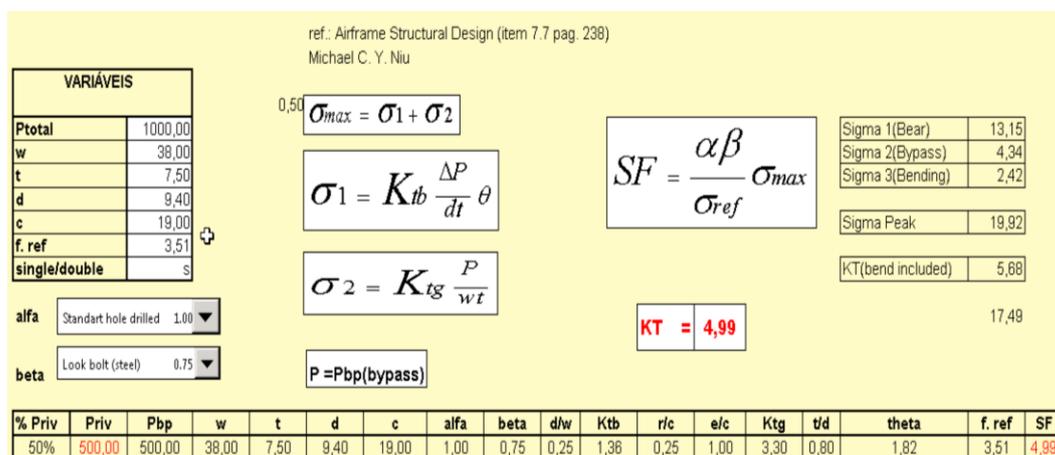
VARIÁVEIS	
Ptotal	1000,00
w	38,00
t	7,50
d	9,40
c	19,00
f. ref	3,51
single/double	s
alfa	Standart hole drilled 1.00
beta	Look bolt (steel) 0.75

ref.: Airframe Structural Design (item 7.7 pag. 238)
Michael C. Y. Niu

$$\sigma_{max} = \sigma 1 + \sigma 2$$

$$\sigma 1 = K_{tb} \frac{\Delta P}{dt} \theta$$

$$\sigma 2 = K_{tg} \frac{P}{wt}$$

P = Pbp(bypass)

$$SF = \frac{\alpha \beta}{\sigma_{ref}} \sigma_{max}$$

KT = 4,99

Sigma 1(Bear)	13,15
Sigma 2(Bypass)	4,34
Sigma 3(Bending)	2,42
Sigma Peak	19,92
KT(bend included)	5,68
	17,49

% Priv	Priv	Pbp	w	t	d	c	alfa	beta	d/w	Ktb	r/c	e/c	Ktg	t/d	theta	f. ref	SF
50%	500,00	500,00	38,00	7,50	9,40	19,00	1,00	0,75	0,25	1,36	0,25	1,00	3,30	0,80	1,82	3,51	4,99

Figure 3. Concentration factor calculation through NIU, 1995. Source: Author.

The value obtained from simulation indicated a K_T = 5.01. This value is not predicted by the literature data. However, it was possible to extrapolate the values, using the combination of K_T = 1 curve and further computation

available on Figure 4. It resulted on a 32.5 kN load, which means 2.5 kN of absolute error, or a relative error of 83 kN from simulation. Also, the K_T had a relative error of 0.4%.
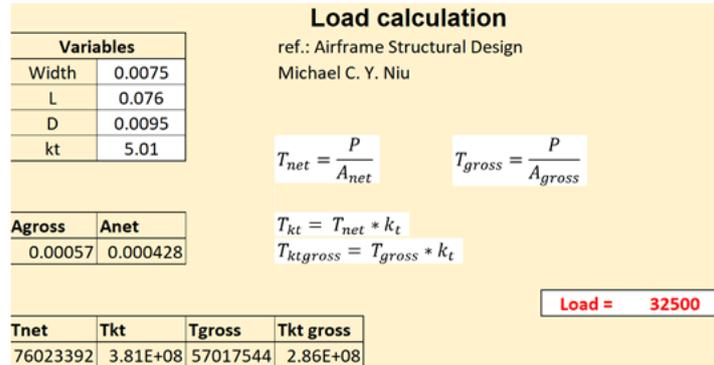

Figure 4. Load calculation through $K_T = 1$ curve extrapolation and NIU, 1995. Source: Author.

Extending the analysis for more effective data regarding the stresses type acting in each specimen model due to the interference between the holes and the pins, another simulation was done through ANSYS®. In this case, just the stress generated by the interference was considered. The geometrical parameters used were the same obtained from the first simulation, despite the holes diameter size, which was assumed as the average between the standard variations proposed. For the HSL type, it was calculated as 9.447 mm, while for the HST, 9.4745 mm. In order to consider the pre-stress generated by the interference, a frictional contact with friction coefficient of 0.2 was adopted between the holes and the pins. The results of this step were presented on Figure 5.
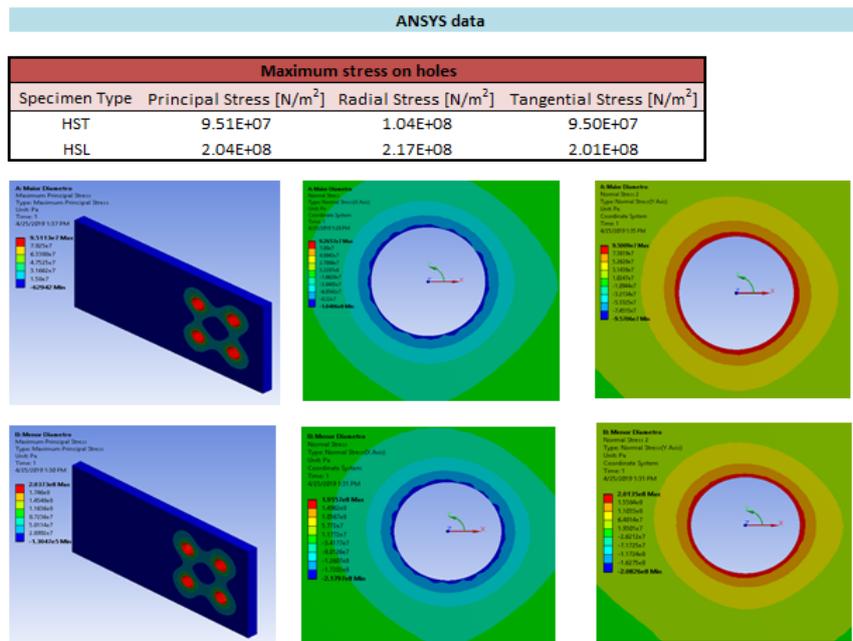
Figure 5. Simulation data on ANSYS®. Source: Author.

With the data provided by the ANSYS® simulation, it was possible to notice that the radial stress indicated compression, within the values of 1.04e+8 N/m^2 for HST and 2.17e+8 N/m^2 for HSL, which indicated 52% improvement on stress from one type to another. Moreover, comparing the tangential stresses, for HST it was obtained as 9.50e+7 N/m^2 and for HSL, 2.01e+8 N/m^2, showing 52% improvement to HSL, again. Finally, comparing the principal stresses on both resulted in 53% improvement for HSL model.

The third part of the work resulted on the physical construction of specimens. From the measurements performed, it was possible to plot the histograms indicating that holes and pins had clearance, respecting the inferior and superior tolerances during the manufacturing process of the 32 tested specimens. Example of the pins is shown below in Figure 6. Moreover, the medium interference of each hole-pin assembly was obtained. It was possible to notice the medium interference on HSL pins was superior to the HST, as expected.
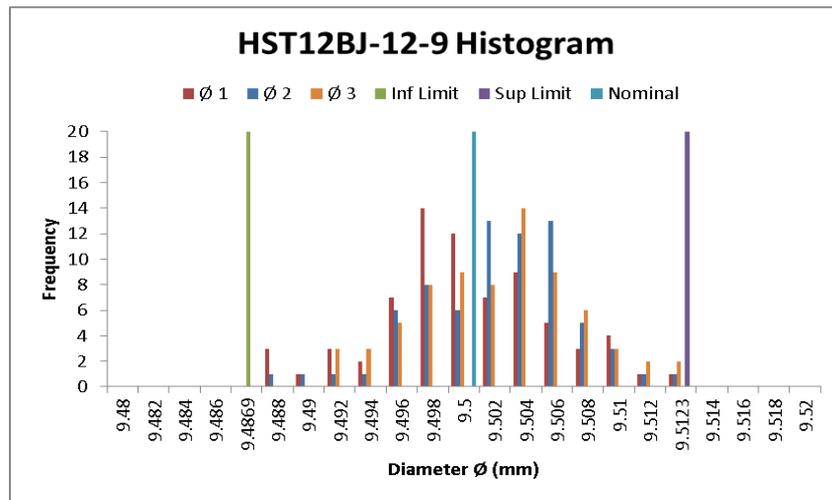
Figure 6. HST pins measured. Source: Author.

Finally, the specimens were tested under fatigue loading. It was possible to notice differences between the input load and the effective load applied, due to machine procedure adopted in order to quickly reduce the load applied and then to start applying it again. This way, the effective load of all specimens corresponded to an average value of 4.6 tons. After cycling the specimens, it was possible to notice the great difference between the numbers of cycles supported on average by each type of specimen, as shown on Tab.1 below.

Table 1. Cycles until rupture for both types of specimens.

Specimen number	Mean Interference Fit for HST (mm)	Mean Interference Fit for HSL (mm)	Number of cycles (HST)	Number of cycles (HSL)
1	0.0152	0.0526	34394	62316
2	0.0234	0.0581	43060	73537
3	0.0235	0.0581	55805	77639
4	0.0257	0.0556	58469	66419
5	0.0187	0.0622	34502	85823
6	0.0253	0.0466	57287	45864
7	0.0231	0.0494	47850	50332
8	0.0224	0.0578	39119	68368
9	0.0244	0.0567	43997	61955
10	0.0263	0.0555	42491	59112
11	0.0266	0.0620	78982	104790
12	0.0231	0.0537	45961	54428
13	0.0203	0.0385	38435	39176
14	0.0143	0.0574	34853	65567
15	0.0249	0.0604	57381	97080
16	0.0228	0.0541	43824	57722

By using the data from Tab.1, it was possible to make comparative histograms between the cases of study, as shown on Figure 7.
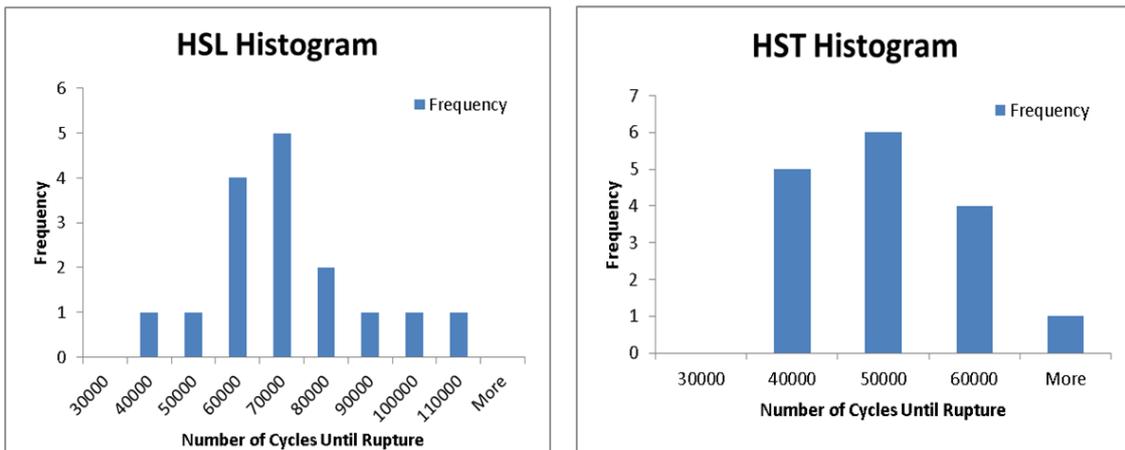
Figure 7. Comparison between HST and HSL cycles until rupture. Source: Author.

Without considering any statistical treatment, the average values for HST and HSL were respectively 63,942 cycles with a standard deviation of 17,701 cycles and 43,911 cycles with a standard deviation of 11,830 cycles to rupture with a 46 kN real load. It leads to a 45% improvement on fatigue life with the cold work use. A hypothesis test was also conducted to check whether the different pins led to different performances or not. This way, Figure 8 shows the distribution of interference fit values for both HSL and HST cases, using the respective hole and pin pairs.
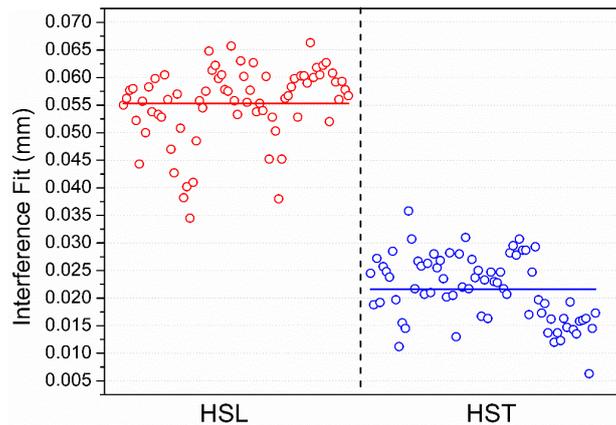

Figure 8. Distribution of interference fit values for both HSL and HST cases and respective mean levels. Source: Author.

As discussed, despite the scattering of the results, the mean interference fit value of the HSL joints seemed to be higher than that accomplished with the HST joints. In order to assure the superior performance of the HSL assembly, the hypothesis of the mean interference fit for HSL assembly being higher than the HSL assembly was carried out through a commercial software for statistics analysis. After processing the data, at a significance level of 0.05, the mean interference fit for the HSL condition was shown to be statistically higher than that of the HST case. This allows assuring with 95% of confidence level that the interference fit of such joining approaches will fall in between the intervals listed on Tab.2 below.

Table 2. Confidence interval for the types of interference fit assessed.

Specimen model	Confidence interval	Lower limit (mm)	Upper limit (mm)
HSL	95%	0.05372	0.05690
HST	95%	0.02017	0.02297

Considering that the HSL approach resulted indeed in a higher interference fit level, the next analysis consisted of verifying whether it effectively led to superior performance or not, regarding the number of cycles of loading in the fatigue test. As seen on Figure 9, the distribution of total cycles before rupture for each sample, with four hole-pin pairs each, resulted in a more scattered data, which justifies the hypothesis test to check the superiority of the HSL assembly.
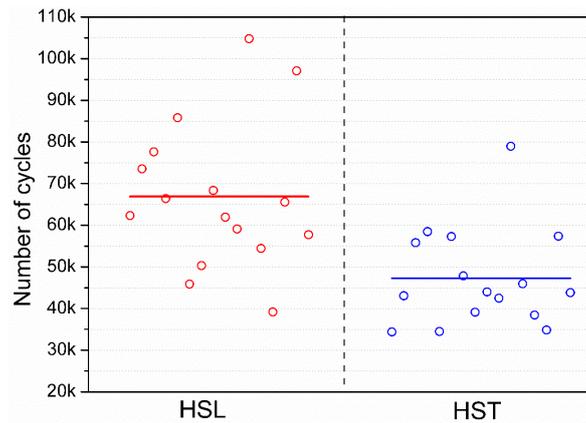
Figure 9. Distribution of number of cycles before rupture for both HSL and HST cases and respective mean levels.
Source: Author.

Thus, the hypothesis tested if the mean number of cycles endured with the HSL assembly was higher than the HST. After processing the data, at a significance level of 0.05, the mean number of cycles endured with the HSL condition is shown to be statistically higher than that of the HST case. This allows assuring with 95% of confidence level that the number of cycles endured with such joining approaches will fall in between the intervals listed in Tab.3 below.

Table 3. Confidence interval for number of cycles before rupture fort the types of interference fit assessed.

Specimen model	Confidence interval	Lower limit (number)	Upper limit (number)
HSL	95%	57,451	76,314
HST	95%	40,971	53,579

So far, by comparing and extrapolating the results out of a linear function for software simulation, obtained as 100,000 cycles within a 30 kN load, it was possible to see an average of 65,217 cycles for the condition proposed. This means a 1.99% of relative error for HSL and 32.67% of relative error for the HST in comparison to what had been predicted by the simulation.

Moreover, the failure mode during tests corresponded to the opening mode of the plate when it is under tension, which represents a failure due to fatigue mechanism. Also, the region where occurred the rupture shows the fatigue marks such as the propagation marks and crack arrest, beginning on the faying surface, as expected from simulations and literature. Figure 10 illustrates these marks for an HSL specimen after the cycling test and rupture.

Figure 10. HSL specimen detail after rupture. Source: Author.

4. COMENTS AND CONCLUSIONS

Cold work presented significant improvements when compared to the lack of any procedure to enhance residual stress around a hole, withstanding 45% more in fatigue life for HSL in comparison to HST specimens. Values were minor than supposed by previous experiments due to different conditions applied to the tests, which included bending, error in machinery, software reading and minor misalignments during the fatigue cycling of specimens. Moreover, the background experiments used the cold expansion technique, which creates more stress on the holes region due to the removal of the mandrel, as discussed.

The extrapolated values for 100,000 cycles and a 30 kN simulated value, within relative errors of 1.99% and 32.67% for HSL and HST specimen types, respectively, can be explained by the exponential curve for K_T which neither predict accurate correlations for calculated $K_T = 5.01$ nor a proper result for single shear joints. Moreover, none of the expectations took into account the bending effect that naturally reduces fatigue life of the component. By taking it into account, HSL performed closer to the expected in comparison with HST specimens, proving that the gain in compressive residual stress guarantees more fatigue life to the component. Considering the data provided by the ANSYS® simulation, it is possible to see that the results showed 52% improvement for HSL in average to all the stresses simulated, indicating that this type of specimen would resist more to the loads applied.

Prediction of load for crack of the specimens was made by two different methods that yielded into a meticulous result, within relative errors of 83 N to the load and 0.4% to K_T. Despite this discrepancy, the model properly simulated the specimen fail mode and higher stresses zone, with crack nucleation and propagation happening due to the tensile opening mode from the faying surface, a mode of failure characterized by fatigue load cycling. Within the statistics analysis, the confidence level of 95% was achieved for the interval of 57,741 and 76,314 cycles for HSL, reassuring the superior fatigue life of this specimen type, while the HST interval varied from 40,971 and 53,579 cycles. Nevertheless, the results were satisfactory to demonstrate that the process has a great potential to be successfully applied in industry for this joint type studied.

5. ACKNOWLEDGMENTS

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