Investigation of Bolt Preload Relaxation for JWST Thermal Heat Strap Assembly Joints with Aluminum-1100 and Indium Gaskets

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Abstract

Accurately predicting fastener preload relaxation in the James Webb Space Telescope (JWST) heat strap assemblies is essential to insure adequate thermal performance during its mission lifecycle. The mechanisms for preload relaxation in the strap joints include Al-1100 material creep, indium gasket flow-out, and embedment of the joint faying surfaces. This report documents the results from a bolted joint relaxation test, including analysis and curve fitting of the test data for predicting preloads five years after initial torque application. The report also includes the derivation of a preload uncertainty factor enveloping both torque/preload application scatter and expected preload relaxation at the end of mission life.

Introduction

The JWST thermal control system includes Al-1100 heat straps for controlling heat flow to and from temperature critical instruments in order to meet instrument performance requirements and optimize observatory science capability. Critical to heat strap performance is preload maintenance at the bolted joint interfaces over mission lifetime. To improve thermal conduction through the bolted interfaces, Al-1100 and indium gaskets are integral in many of the joints. Although these materials are common for improving thermal conduction in aerospace bolted joints, Al-1100 creeps under load at room temperature and indium gaskets can gradually flow out. Creep and flow-out will relax joint preload and therefore degrade joint thermal conductance over time. Many of the heat strap joints also include threaded inserts in Al-1100, resulting in high stresses in the parent material around the insert and exacerbating Al-1100 creep. Figure 1 illustrates a representative flight joint for the JWST heat strap assemblies.

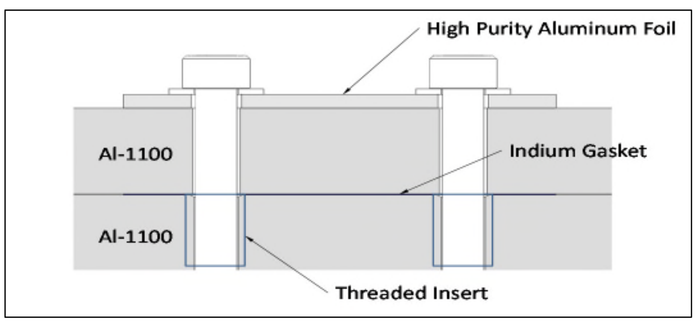

Figure 1. Representative Heat Strap Bolted Joint Interface

Because Al-1100 is relatively low in strength, compression of Al-1100 under washers and threaded insert pull-out limit the design space for the initial bolt preload. This limited design space necessitates a rigorous approach for predicting joint preloads in the heat straps throughout the joint life cycle.

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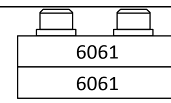
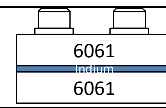
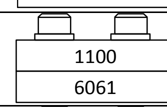
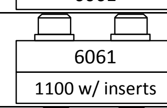
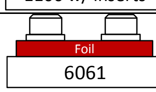
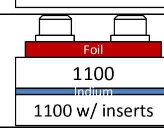
In order to quantify preload loss over time, a comprehensive joint relaxation test was completed. The test includes a set of representative flight-like joints, a control set, and various joint configurations in order to compare preload loss between different drivers for joint relaxation. The different joint coupons were torqued to the same nominal preload and the preload relaxation was measured over a period of eight months. The test data was then processed in an Excel spreadsheet for future preload loss predictions. Uncertainty factors were also derived for calculating max and min expected preloads, accounting for both scatter in initial preload application and joint relaxation over time.

Test Description

Table 1 lists the joint configurations tested. For each group, with the exception of the control group, a set of 3 coupons were tested with the bolts re-torqued 24 hours after the initial torque-up and a set of 3 coupons were not re-torqued. For the control group, only 3 coupons were tested without any re-torqueing of the bolts. The coupons included #10-32 A-286 fasteners, phosphor-bronze threaded inserts (2D length), and lubrication of external/internal threads with Braycote. All coupons were torqued to a nominal preload of 1550 N (350 lbf).

Table 1. Coupon Test Configurations

Configuration	Description	
Control	Al-6061 top plate compressed against an Al-6061 bottom plate	
Indium	0.005-in (0.13-mm) thick Indium foil between Al-6061 plates	
1100C	Al-1100 plate compressed against an Al-6061 bottom plate	
1100T	Al-6061 plate bolted into an Al-1100 plate, putting threads in tension	
Foil	Multiple layers of 0.002-in (0.05-mm) thick high-purity aluminum (99.999% Al) in direct compression against an Al-6061 bottom plate	
Flight	Combines multi-layer aluminum foil in compression, 1100 plate in compression, Indium in compression, 1100 in tension	

All test coupons included a FUTEK piezo-electric load cell for preload monitoring. The data acquisition system included the SENSIT Test and Measurement Software. The program was set to sample load cell outputs every 0.1 second during initial torque-up for each joint. After initial torque-up, the load cells were sampled every 10 minutes. Test data was downloaded on a daily basis for monitoring and analysis. A separate load cell was put under a known weight and monitored for several months to confirm that the load cell read-out did not drift over time.

Joint Relaxation Test Data Analysis

The physical mechanisms driving preload loss in a thermally conductive bolted joint with Al-1100 and an indium gasket are varied and complicated, making it difficult to derive a simple mathematical model for predicting joint relaxation. An alternative approach is to curve fit data from a joint relaxation test and extrapolate the empirical model for predicting future preload loss. After curve fitting the test data with several candidate functions, the natural logarithm function proved to be the most accurate for fitting the data across the various coupon test configurations.

Using the method of least squares, the data was processed in Excel and the software's Solver Tool was applied for minimizing the sum of the chi square values (the square of the difference between the real data and the predicted data). Since the data acquisition system sampled preload every 10 minutes for 32 joint coupons and the test duration was more than 8 months, the spreadsheet was set up to sample the test data every 24 hours. This minimized the processing time for each Solver Tool run and kept the spreadsheet at a manageable size. A number of curve fits were also processed with higher analysis sampling rates in order to check the nominal analytical sampling rate. Additionally, the coefficient of determination (R^2) was calculated for each curve fit to quantify how well the test data fit the curve. Figure 2 is a plot of the test data and curve fit for the Flight-1 coupon.

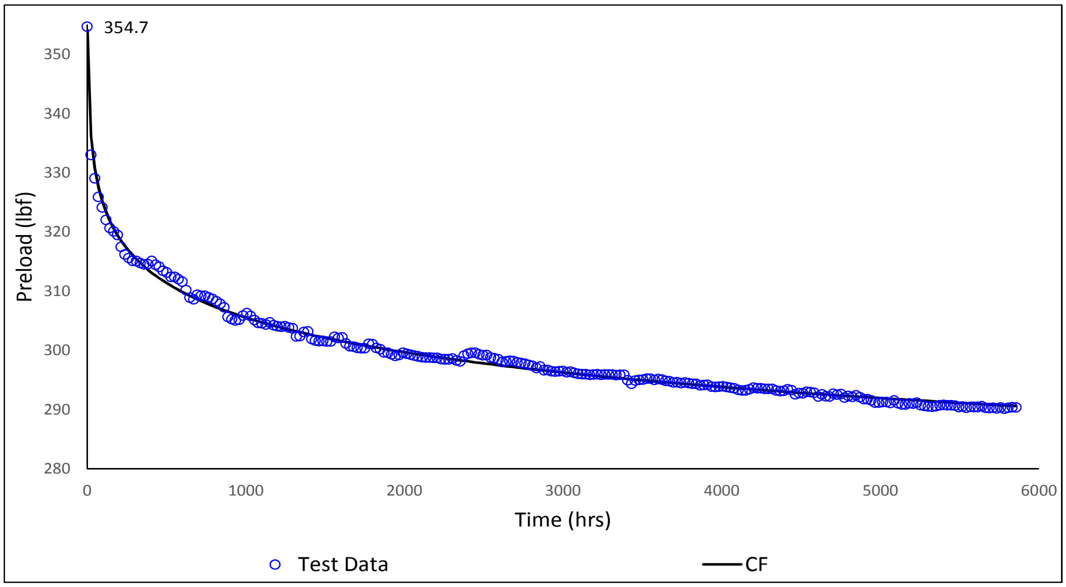


Figure 2. Test Data and Curve Fit for Flight-1 Coupon

Joint Relaxation Test Results

Figure 3 plots the average preload predictions after 5 years, with 2-sigma error bars calculated from the test data. The results from this test are specific to the joint configurations tested (materials, thicknesses, configurations, initial nominal preload, etc.) and apply only to these specific configurations. Caution should therefore be exercised when extrapolating the results to design deviations from the specific configurations tested. As can readily be seen in Figure 3, the flight configuration (with 1 re-torque), is predicted to lose ~25% of its initial preload (average + 2-sigma). Without the re-torque, the preload loss is >40%. For comparison, the control configuration, a typical joint for structural applications in flight and ground support hardware, is predicted to lose ~5% of its initial preload after 5 years. The test results also show that the biggest drivers for joint relaxation are the Al-1100 in tension (inserts embedded in Al-1100) and the high-purity aluminum foil in compression. Joint relaxation from indium flow-out appears to benefit the most from a single re-torqueing of the bolts (from ~25% to <10%).

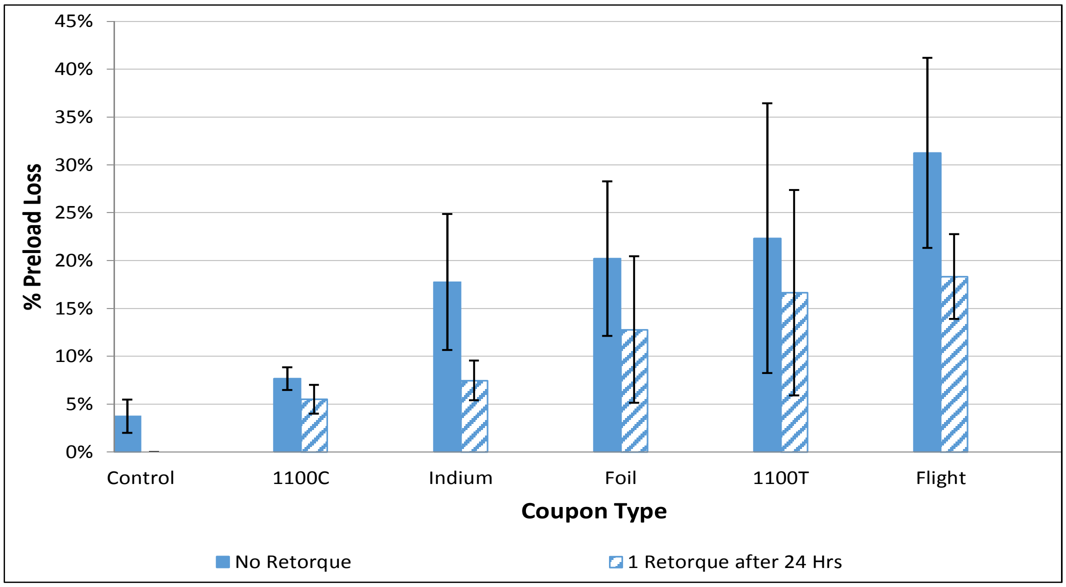


Figure 3. Joint Relaxation Preload Loss Predictions (5 years out)

The plot in Figure 4 compares the curve fits for the different configurations. The plots only include the coupons that were re-torqued, with the exception of the control coupons. Figure 4 shows the curve fits for preload loss after approximately 6000 hours of testing (~8.3 months), the flight coupons were losing ~0.25 lbf (1.1 N) of preload per week and the control group was losing <0.1 lbf (0.4 N) of preload per week.

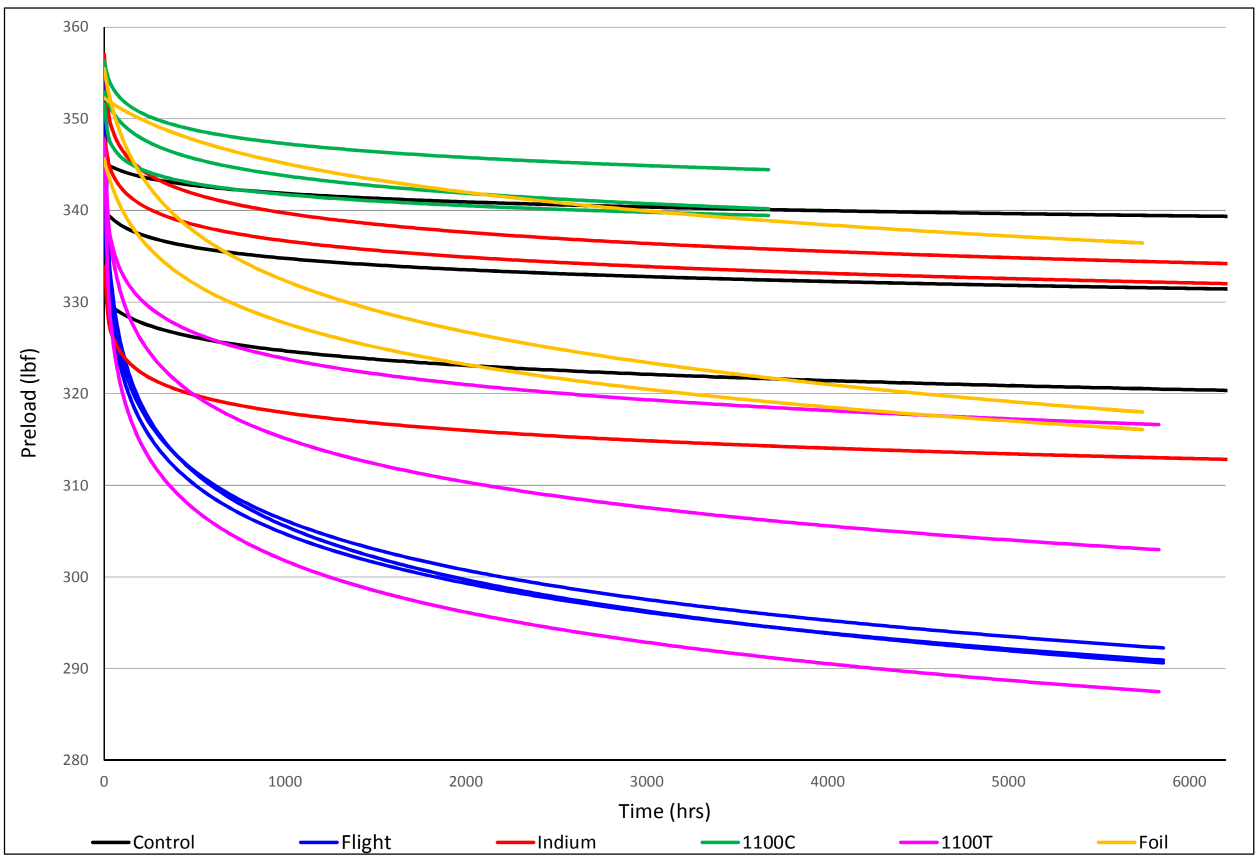


Figure 4. Curve Fits for Preload Loss Over Time

Preload Uncertainty Factor

A torque/preload uncertainty factor (UF) is typically included in bolted joint analysis for calculating the expected maximum and minimum preloads after torque application to a design nominal preload. The UF for a given joint configuration can be recovered from torque/preload test data with the assumption that the preload probability distribution function (PDF) is Gaussian. NASA-STD-5020 [1] recommends the recovery and use of a B-basis (90% of population with 95% confidence) UF for bolted joint analysis.

In addition to the torque/preload UF, the calculated max/min preload must also account for preload loss over time, especially when preload is critical for joint performance. A total UF, accounting for the scatter in preload from both the initial torque-up of a bolt and relaxation over time, is derived in order to simplify the final bolted joint analysis and retain the use of existing in-house analysis programs. Preload changes due to temperature effects are not included in the UF since it is calculated separately.

In order to easily combine the preload scatter for the nominal installation preload and joint relaxation, the PDF for preload loss from joint relaxation is assumed Gaussian and independent from the initial torque-up preload PDF. This is a reasonable assumption if the torque/preload UF is low. The average relaxed preload after torque-up and preload loss is simply the nominal initial preload minus the average predicted preload loss across all coupons for a given configuration.

$$Preload_{relax\_average} = Preload_{nom}\left(1 - \%Loss_{average}\right) \tag{1}$$

Since the initial preload and preload loss are uncorrelated random variables and their PDFs are Gaussian, the B-basis UF for the relaxed preload PDF is simply the RSS (root sum square) of the UF values for the initial preload PDF and preload loss PDF.

$$UF_{relax} = \sqrt{UF_{initial}^2 + UF_{loss}^2} \tag{2}$$

A total UF^- can then be derived for the minimum expected preload.

$$Preload_{min} = Preload_{nom}\left(1 - \%Loss_{average}\right)(1 - UF_{relax}) \tag{3}$$

$$Preload_{min} = Preload_{nom}\left(1 - \%Loss_{average} - UF_{relax} + \%Loss_{average}UF_{relax}\right) \tag{4}$$

$$Preload_{min} = Preload_{nom}(1 - UF^-) \tag{5}$$

$$UF^- = \%Loss_{average} + UF_{relax} - \%Loss_{average}UF_{relax} \tag{6}$$

Figure 5 illustrates the relationships between UF^- and the nominal preload.

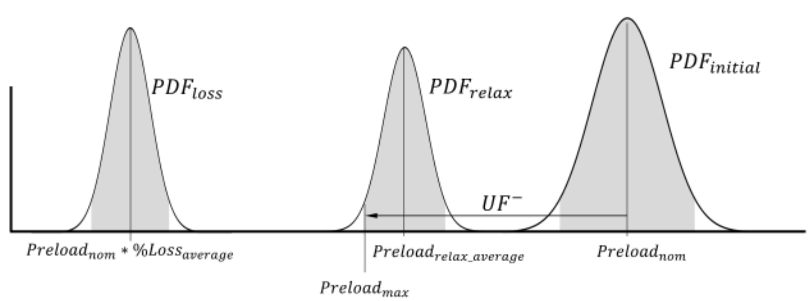


Figure 5. UF^- and Nominal Preload

UF^+ is simply equal to the torque/preload UF, since the max preload for any given time is before joint relaxation progresses.

$$Preload_{max} = Preload_{nom}(1 + UF^+) \tag{7}$$

$$UF^+ = UF_{initial} \tag{8}$$

Table 2 summarizes the calculation for the total UF to be applied to the nominal preload loss at room temperature for the heat strap flight joints at specified intervals after re-torque. It is noted that re-torque decreases UF^- from 0.69 to 0.52 for the expected minimum preload after 5 years. Calculations are based on a torque/preload UF of 0.36, which was determined from a separate nut factor test for this bolt/insert flight configuration.

Table 2. Total Preload UF for Flight Joints After Re-torque

Coupon	Retorque	Max Preload (lbf)	% Preload Loss from CF		
			after 24 hrs	after 5 years	after 13 years
Flight-1	Y	354.7	4.9%	22.9%	25.1%
Flight-2	Y	344.5	3.1%	20.1%	22.3%
Flight-3	Y	341.4	1.6%	19.1%	21.3%
		Average	3.2%	20.7%	22.9%
		Sigma	1.7%	2.0%	2.0%
		B-basis Prealod UF (Torque/Preload)	0.36	0.36	0.36
		B-basis Preload UF (Loss)	0.14	0.14	0.16
		Preload UF (Relax)	0.39	0.40	0.40
		UF(+)	0.36	**0.36**	0.36
		UF(-)	0.41	**0.52**	0.54

Conclusion

A joint relaxation test was completed, specific to the JWST heat strap attachment joints. The flight joints include threaded inserts embedded in Al-1100, washers bearing directly on high purity aluminum foils, and indium gaskets. Al-1100 is known to creep under load at room temperature and indium gaskets can gradually flow out of a bolted interface. The results of the test and post-test processing of the data show that the flight joints can lose ~ 25% of its initial preload (average+2-sigma) in 5 years after initial torque application. A relative high torque/preload UF of 0.36 was also determined based on a separate test for bolts with threaded inserts in Al-1100. Combining the results from the joint relaxation test and a separate torque/preload test, a total uncertainty factor of 0.52 was calculated for the minimum expected preload in a flight joint five years after initial torque-up. In other words, the minimum expected preload five years after initial torque application is 52% of the nominal installation preload. The test and data analysis results presented in this report has been applied to the JWST heat strap attachment joint analysis for predicting preloads and checking thermal performance requirements.

Several observations are noted from the test results and curve fits. The largest relaxation drivers in the heat strap joints are (1) threaded inserts embedded in Al-1100 and (2) washers bearing directly on high purity aluminum foils. Also, pull-out strengths for inserts in Al-1100 are low due to the very low shear strength of the parent material which further reduces the design space for the attachment joints. It is recommended that threaded inserts in Al-1100 are avoided if possible in future joint designs. Alternate options for joints requiring Al-1100 members for thermal performance could include nuts or nut plates. The test results also demonstrate the benefit of re-torqueing bolts in joints that include indium gaskets. For the indium and flight joint coupons, re-torque after initial torque-up reduced the total preload loss (5 years out) by ~50%.

Caution must be exercised when applying the results from this test to joint configurations that deviate from the JWST heat strap joint designs (material, initial torque, indium gasket, bolt size, etc.). It is recommended that the results in this report are not directly applied to other joints configurations, but may be used for guidance and insight when designing joints with similar configuration.

References

1. NASA, "Requirements for Threaded Fastening Systems in Spaceflight Hardware", NASA-STD-5020