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Fastener investigation in JET

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HIGHLIGHTS

- Experimental work to identify the cause of a bolt seizure inside the JET vessel.
- Taguchi method used to reduce tests to 16 while covering 5 parameters.
- Experimental work was unable to reproduce bolt seizure.
- Thread contamination had little effect on the bolt performance.

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ABSTRACT

JET is an experimental fusion reactor consisting of magnetically confined, high temperature plasma inside a large ultra-high vacuum chamber. The inside of the chamber is protected from the hot plasma with tiles made from beryllium, tungsten, carbon composites and other materials bolted to the vessel wall. The study was carried out in response to a JET fastener seizing inside the vacuum vessel.

The following study looks at characterising the magnitude of the individual factors affecting the fastener break away torque. This was carried out using a statistical approach, the Taguchi method: isolating the net effect of individual factors present in a series of tests [1](Grove and Davis, 1992).

Given the severe environment within the JET vessel due to the combination of heat, ultra-high vacuum and the high contact pressure in bolt threads, the contributions of localised diffusion bonding is assessed in conjunction with various combinations of bolt and insert material.

1. Introduction

During the 2012 JET shutdown, several tiles were removed by remote handling (RH) for maintenance and analysis. It was found that on many tiles the breakaway torque (torque required to loosen a bolt) on the fasteners had increased beyond the initial tightening torque, typically by two times.

One Inconel 718 fastener could not be undone applying a torque of 80Nm, the maximum torque capable from the RH tool. Given the tightening torque was 35Nm, this bolt was assumed to have seized. Reasons for this occurring are unknown however the combination of heat, ultra-high vacuum (UHV) conditions and high external loading are believed to have contributed.

There are many points to consider when examining the operational capabilities of the bolted assemblies within the JET vacuum vessel. Observations were made that the use of Spiralock® thread, thread coatings and heat loading can have an effect on the performance of the bolts within JET [2].

Testing of bolted assemblies has largely involved testing vast quantities of components to individually isolate the effect of the experimental parameters within the tests [3].

The scope of this study is to examine the effects of the variables present in a bolted assembly and to determine the most likely cause of the seizure.

Fig. 1 shows both the individual parts and a built assembly representative of those used during testing. The assembly consists of a bolt, three Inconel 718 disk spring washers, an Inconel 625 spacer and a threaded insert.

The bolt material was varied to determine whether Nimonic 80A may be more suitable than Inconel 718.

Contamination was applied to the bolt in the form of crushing sections of the thread and submerging the bolt in machining cutting fluid before the standard JET cleaning procedure was carried out on the bolts. This would determine whether poor handling of bolt prior to installation was the cause of bolt seizure.

The examination of the effects of the experimental parameters was achieved by using a statistical approach based on a Taguchi

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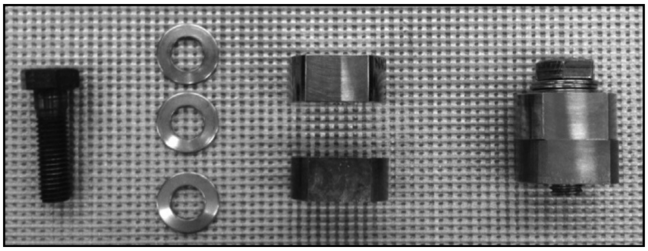

Fig. 1. Bolt assembly.

method of examining interactions between test factors [1]. The motivation for taking this approach was to reduce the number of tests and in turn reduce the cost and time required to carry out the study.

Here we wish to examine the effect of 5 factors each of which can have two states. For example, factor 1 is the bolt material which can be either Nimonic 80A or Inconel 718. A full experimental study would thus require 32 tests (2^5). The Taguchi method guides the selection of a reduced number of factor combinations to be used in a smaller number of tests – 16 in this case – to maximise the output from the tests.

The method of selecting the state of each parameter in each test is aided by the orthogonal array shown in Fig. 2. The L16 orthogonal array is a standard predetermined pattern. The columns represent a position in which a parameter may be assigned. The rows represent a test. For a given test, the sign in the column determines the state the corresponding parameter will be for that test.

For the case where 4 factors are being tested, the number of tests required is 16 (2^4). In the L16 array, the corresponding columns in which the four parameters would be assigned are; 1, 2, 4 and 8.

The use of 4 factors assigned to an L16 array is an example of a full factorial experiment. The results would be shown to have well defined effects present which are due to the variance of the parameter states. In an effects plot, the output of this analysis, the measured effect from each parameter would be well defined and no interference on the result would be present, except for small experimental errors from anomalous results.

However in some columns, where a parameter is not assigned, there will be measured effects present. This occurs when the mixture of two columns in the orthogonal array is equal to that of another. For example, in Fig. 2, when columns 1 and 2 are combined, they are equal to that of column 3. This measured effect would be due to an interaction of two parameters. If the two parameters do not have an effect on each other, the measured effect shown in column 3 should be small.

The inclusion of these 2 factor interactions does not cause a problem in a full factorial experiment. However the inclusion of a 5th parameter, as seen in this study, means that interference between measured effects is present. This is known as a fractional factorial experiment.

The impact this will have on the results can be described using Table 1, where the factor interactions for the given assigned parameters can be seen.

In column 4 of Table 1, we can see that parameter D was assigned. However, because the additional 5th factor was assigned to column 5, there is now an associated 2 factor interaction (2FI) present that may affect the measured effect. The overall measured effect may be expressed as: [D] + [AE].

Whilst there is no way to determine the proportion of the measured effect which is due to both the pure effect and the effect due to the 2FI, judgement is required to determine whether the parameters associated with the 2FI are capable of causing a measurable effect.

This is the compromise made when using a fractional factorial experiment design, a reduction in the resolution of results.

Five of the columns represent the test factors and those remaining are left un-assigned but are used for statistical analysis as described later.

Here the columns were assigned as follows:

- 1 (A) – Bolt material (Nimonic 80A/Inconel718)
- 2 (B) – Contamination (Yes/No)
- 4 (D) – Insert Material (Inconel 625/NAB)
- 5 (E) – Insert thread form (ISO Standard/Spiralock®)
- 8 (H) – Heat Cycle (Yes/No).

The assignment of the factors to their columns was carried out by first assigning the baking parameter to column 8. The basic method of the experiment was to carry out a tightening-loosening operation on the bolt, then carrying out a heat cycle on the bolts whilst tightened and then loosen once the cycle was complete. With the heat cycle placed in column 8, this would allow the first 8 tests to represent the un-heated tests and the final 8 to be the heat cycled tests.

Due to the pattern of the orthogonal array, the remaining parameters had to be assigned in the columns to the left of column 8 to ensure that the test parameters remained the same both before and after the heat cycle.

TESTS	PARAMETERS/EFFECTS 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-	-	+	-	+	+	-	-	+	+	-	+	-	-	+
2	+	-	-	-	-	+	+	-	-	+	+	+	+	-	-
3	-	+	-	-	+	-	+	-	+	-	+	+	-	+	-
4	+	+	+	-	-	-	-	-	-	-	-	+	+	+	+
5	-	-	+	+	-	-	+	-	+	+	-	-	+	+	-
6	+	-	-	+	+	-	-	-	-	+	+	-	-	+	+
7	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+
8	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-
9	-	-	+	-	+	+	-	+	-	-	+	-	+	+	-
10	+	-	-	-	-	+	+	+	+	-	-	-	-	+	+
11	-	+	-	-	+	-	+	+	-	+	-	-	+	-	+
12	+	+	+	-	-	-	-	+	+	+	+	-	-	-	-
13	-	-	+	+	-	-	+	+	-	-	+	+	-	-	+
14	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
15	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Fig. 2. L16 Orthogonal Array.

Table 1
Factor Interaction Table.

Column no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Effect	[A]	[B]		[D]	[E]			[H]							
Measured 2FIs	[DE]		[AB]	[AE]	[AD]	[BD]	[BE]		[AH]	[BH]		[DH]	[EH]		
Measured 3FIs			[BDE]			[ABE]	[ABD]		[DEH]		[ABH]	[AEH]	[ADH]	[BDH]	[BEH]
Measured 4FIs											[BDEH]			[ABEH]	[ABDH]

Fig. 3. Vacuum Furnace.

The bolt material, contamination and insert material parameters were then assigned to columns 1, 2 and 4, the same for a full factorial experiment. The insert thread form parameter was then placed based on the position which would lead to fewer 2 factor interactions and thus, results with the highest resolution. Table 1 shows the parameter placements used and the associated 2, 3 and 4 factor interactions.

2. Materials and methods

The experimental testing involved the following test procedure:

1. Bolt relaxed – Length measured
2. Bolt tightened to 35Nm – Length measured
3. Bolt loosened – Length and breakaway torque measured.
4. Bolt tightened to 35Nm – Length measured
5. Bolt loosened – Length and breakaway torque measured.
6. Bolt tightened to 35Nm – Length measured
7. Bolt loosened – Length and breakaway torque measured.
8. Bolt tightened to 35Nm – Length measured. Bolt vacuum baked for 7 days at 380 °C.
9. Post bake – Length measured.
10. Bolt loosened – Length and breakaway torque measured.

At each stage of the procedure the tightening/loosening torque of the bolted assembly was measured using a digital torque wrench which records the maximum values. In addition to this, the lengths of the bolts were measured using micrometer at each stage to enable the inference of a bolt preload prior to loosening. To obtain the most accurate length measurement, the bolts were modified before testing began to have machined flat surfaces on the top and bottom surfaces. When used in conjunction with stiffness values obtained through both hand calculation and finite element analysis, the preload of the bolt may be inferred.

The heat cycle consisted of placing the assemblies into a vacuum furnace (Fig. 3) pumping down to 1×10^{-6}mbar and heating to a predetermined temperature of 380 °C. This temperature was selected as it is a representative value of that expected in the JET vacuum vessel during operation.

3. Results

The baseline test consisted of the following parameter states:

- Bolt material – Inconel 718.
- Contamination – Yes.
- Insert Material – Nickel-Aluminium-Bronze (NAB).
- Insert thread form – Spiralock®.

This represents the standard fixing configuration used in JET, with the added contamination procedure applied to the bolt. Fig. 4 represents the raw breakaway torque data, combined with the calculated k-factor data for the baseline case. The k factor may be obtained for values of applied torque, bolt diameter and bolt preload.

$$T = k \times F \times D$$

T = Applied torque k = Bolt torque factor
F = Bolt preload D = Bolt diameter

Fig. 5 represents the length data collected from the baseline test. Plot alongside it is the inferred bolt preload, based on stiffness values from finite element analysis data.

4. Discussion

In order to calculate the net effect of each of the parameters, the average response, in this case breakaway torque, must be calculated from all results, i.e. all responses from each data set. Each data set consisted of a response from each of the defined tests. For each of the tests, 2 replicate tests with the same parameters were also carried out. This was to enable the mitigation of an anomalous result by averaging the three results.

This creates the reference value from which the net effects will be plotted either side of, as seen in Figs. 6 and 7.

To obtain the net effect of a particular parameter, the average value of all the responses with a "+" must be subtracted from all the average responses with "–". This then gives the range of the net effect between the two states of the chosen parameter.

Fig. 6 shows the bolt length effects plot and Fig. 7 the effects plot of the breakaway torque data for the same set of bolt tests.

Fig. 6 shows that the largest effect on preload is the heat cycle, followed by insert thread form.

Due to the interactions in each column, summarised in Table 1, it can be determined that the large net effect seen in column 8 for the heat cycle is a pure effect, i.e. not the result of confounding 2 factor interactions. This then suggests that the heat cycle is the cause of the largest reduction in bolt preload out of all the effects studied.

Whilst the other columns in Fig. 6 do show small effects by comparison, they are confounded by two factor interactions and it is difficult to determine the extent of which the 2 factor interactions affect the pure effect they are confounding.

However, what may be observed is that there are net effects in columns which have no pure effects assigned to them. This shows that there are interactions between factors. The most significant example of this in Fig. 6 is column 12, a result of the heat cycle and insert material. The net effect observed is equivalent to that of

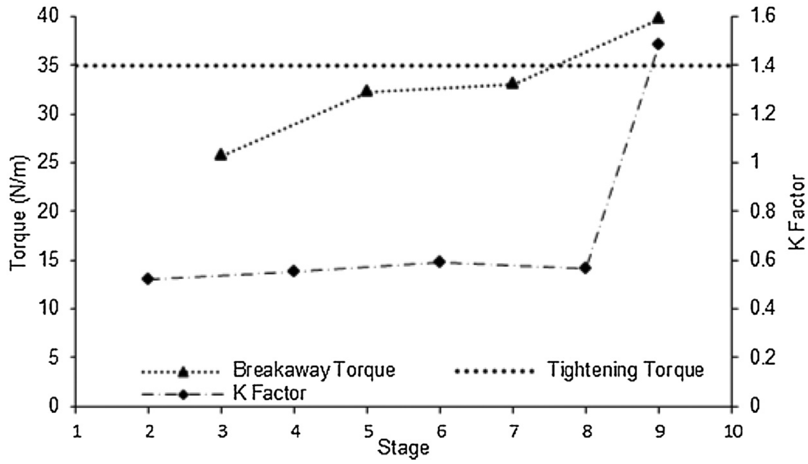

Fig. 4. Sample Torque and K factor data.

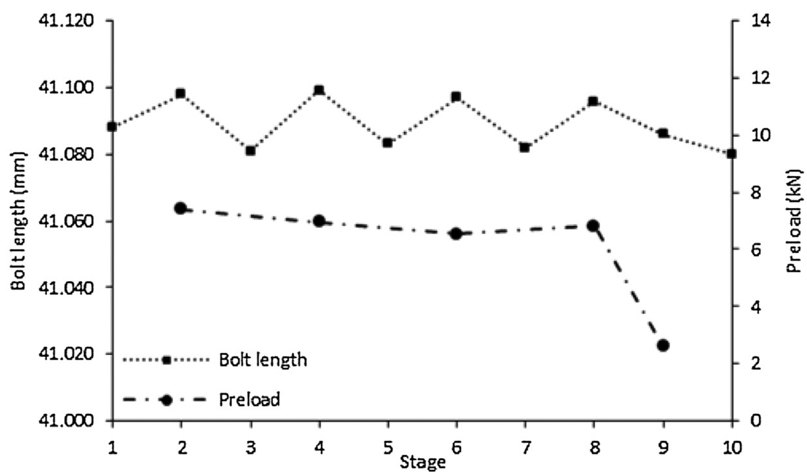

Fig. 5. Sample Bolt Length and Preload Data.

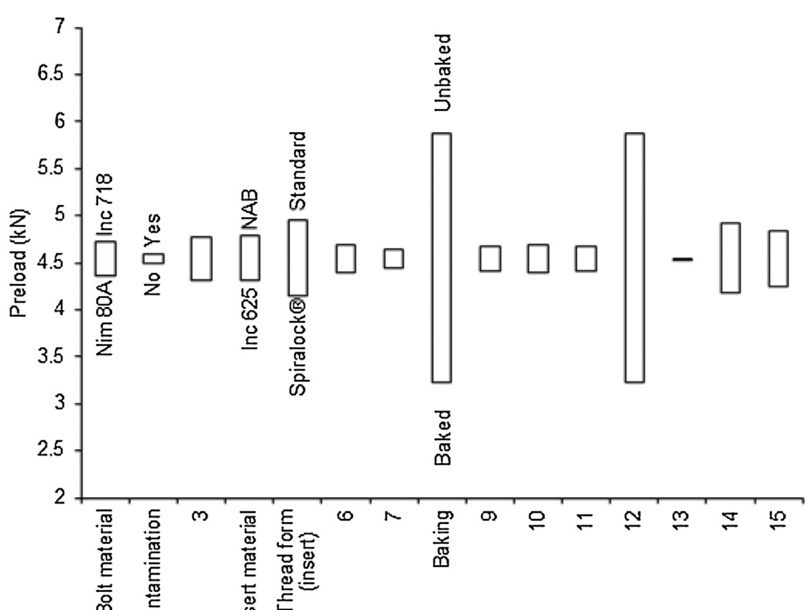

Fig. 6. Bolt Preload Response Effects Plot.

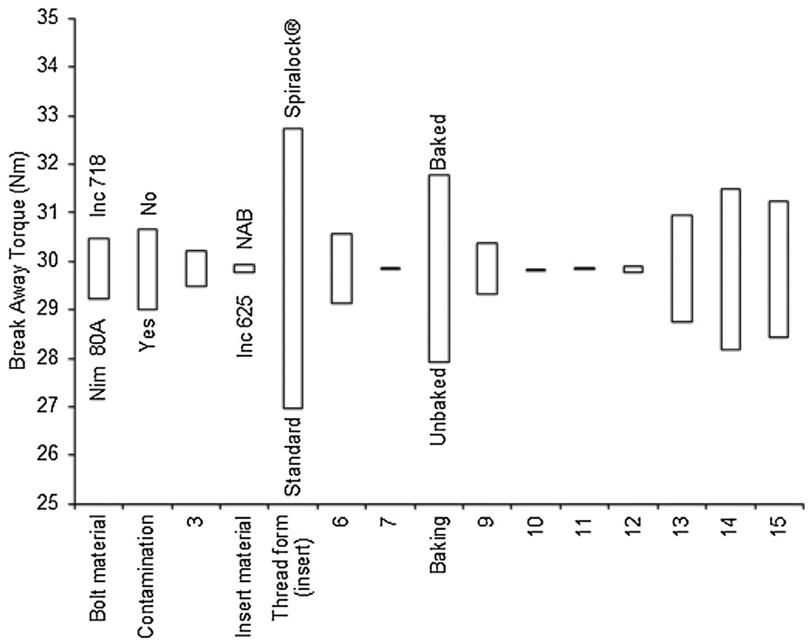

Fig. 7. Breakaway Torque Response – Effects Plot.

the heat cycle. This may indicate that the interaction present, given that the insert material is so small, is a significant one.

Crucially however, column 2 in Fig. 6 which displays the pure effect of bolt contamination shows that this does not have a relatively large effect on the preload of the bolt. This helps to rule out that the bolt seized in the JET vacuum vessel due to damage or contamination of the bolt.

Further to the interactions not present in pure effect columns, there are some present in columns 14 and 15. This is also an interesting observation, as it demonstrates that 3 factors may combine and display a measurable effect.

Previously at JET, a k factor of 0.3 has been assumed for preload calculations in the absence of any measured values giving a preload of 11.7 kN for 35Nm. However, the As Manufactured bolt tests have shown that the preload is significantly lower than this value, the average value being on 6 kN before baking.

The predicted preload is further reduced to about 3 kN by the baking process at 380 °C.

Fig. 7 shows that the two greatest influences on breakaway torque are insert thread form and baking. They are closely followed by bolt contamination and bolt material. Note that the scale in Fig. 7 has been altered to show a false origin to emphasise the relative difference in effects. Column 5 which shows the effect of insert thread form shows a relatively large variation when compared to other effects. However, this is an effect of ~20% on the breakaway torque.

As described for Fig. 6, column 8 represents the pure effect of the baking cycle with no confounding effects. Indicating that the baking cycle does have a measurable effect on breakaway torque. The other pure effect previously mentioned is bolt contamination, seen in column 2. Against what was expected, it was observed that by having a bolt damaged/contaminated reduced the breakaway torque; the reasons for this are unknown. The effect represents a ~5% change in breakaway torque and so not very significant.

The largest net effect seen in column 5 is the insert thread form. Whilst this column is confounded by bolt material and insert material, these two effects are much smaller than the net effect shown column 5. Unless these two effects serve to magnify one another when combined, it is likely that the majority of the net effect shown is due to a genuine effect caused by the changing of insert thread form. The real effect seen in this column suggests that the Spiralock® thread increases the breakaway torque as expected whilst with the standard thread it is less.

The breakaway torque data post bake has increased beyond the tightening torque however not as much as expected (Fig. 4). This is believed to be due to a multitude of factors. Firstly, the bolt preload is not reaching the expected higher levels (possibly due to the oxide layer causing a large source of friction). Secondly, due to the preload being reduced during the baking process the bolt is relaxed and not recovering, therefore reducing the torque required to breakaway.

5. Conclusions

In this study, the in-vessel conditions which led to a bolt seizure were not replicated: the breakaway torques seen post bake were not double those pre-bake. This would suggest that there is another effect present in the JET vacuum vessel other than UHV conditions and elevated heat levels.

An additional aim of the study was to explore the possibility of using Nimonic 80A as a bolt material in this particular application where Inconel 718 bolt have been used for strength. The results shown are inconclusive. Whilst Inconel 718 has the higher preload (Fig. 6), Nimonic 80A has the lower breakaway (Fig. 7). This issue will be revisited in a future study.

Acknowledgments

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