High temperature life prediction of a welded IN718 component

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Abstract. Life predictions from a case study of a welded feature in a generic spoke structure, determined using three-dimensional quasi-static elastic-plastic and creep finite element analyses, are demonstrated. The complete structure consists of multiple Inconel 718 (IN718) TIG-welded features; the welds exhibit noticeably depleted mechanical properties so a multi-material analysis is necessary for accurate predictions. The effect the welds have on the life is investigated for both constant (creep) and cyclic loading (creep-fatigue) conditions at 620°C. Creep damage and Smith, Watson and Topper (SWT) strain parameter lifing methods are used, based upon material properties determined using uniaxial test data. The lower fatigue properties of the welded IN718 material at high temperature had a negative effect on the fatigue life of the structure. The effect of the weld on the life under constant loading at high temperature was found to be more difficult to evaluate due to significant stress relaxation.

1. Introduction

Structures that are subjected to high service temperatures where creep (and possibly creep-fatigue) is significant need well defined material behavior and for all integral structural components, the lifetime requires assessment. For this case study, a thin-section generic spoke structure was analyzed to demonstrate the application of high temperature lifing methodologies to a complicated geometry including a weld with differing material properties. Comparisons are then made to identify how the inclusion of the weld affects the life of the structure.

Life assessment of welded thin-section structures is particularly complex due to residual stresses, distortions and material microstructural changes caused by the welding process. In particular, out-of-plane distortions compromise uniaxial material testing. The weld bead geometry must also be considered (if present) since sharp fillet radii result in high stress concentrations at the weld bead and parent interface. Due to these factors, the weld has a direct effect on the creep and fatigue life [1].

Although it has disadvantages such as those mentioned above, welding (as opposed to casting) reduces the cost of large structural components and can eliminate the need to transport full size cast components from the supplier to the manufacturer, which is also more cost efficient and better for the environment. As such, welding is an integral manufacturing procedure for many components, some of which could not be produced without its application.

The material used throughout this study was sheet Inconel 718 (IN718), a precipitation-hardenable, niobium-modified, nickel-base superalloy that is used extensively in the aerospace, petrochemical, and nuclear industries since it exhibits good strength, excellent resistance to oxidation at high temperatures and favorable weldability. The material properties and failure behavior for both parent and weld material were determined from specimen testing, which is briefly summarized here; more information
on the fatigue testing can be found in [2]. The temperature for the testing and the subsequent life assessment analyzes was 620°C, since this is the temperature limit permitted for many critical applications of the material [1].

2. Material property testing
As mentioned above, it is desirable to avoid weld-induced distortions, particularly when material properties need to be determined through conventional uniaxial testing. For test specimen manufacture, the distortions can be effectively mitigated by only welding small plates that are just large enough to form one test specimen. The small size increases the relative stiffness of the plates, and reduces the welding time and therefore the time at which nonuniform thermal expansion exists, which is the driving force of the distortions. Unlike other methods of distortion prevention, such as those involving trailing heat sources or sinks, this solution does not modify the effects of the welding process on the thermal history of the material. If the plates remain flat after welding, the stress-concentrating weld bead excess can be removed by a linishing process.

Both non-welded and TIG butt-welded bow tie specimens were manufactured from a 3.2mm solution heat treated sheet of IN718 provided by Haynes International Ltd. Mechanized, fully penetrating, single pass TIG, square-edge, closed butt welds, were made between the short sides of 100mm x 40mm coupons with matching IN718 filler wire and argon shielding. The small welded plates did not distort and weld bead excess was removed without difficulty. After bow tie profiling and prior to polishing, all specimens were given the same precipitation heat treatment before testing, consisting of: 720°C/8hrs, 50°C/hr furnace cool to 620°C/8hrs, air cool. This heat treatment also effectively relieves welding-induced residual stresses [3].

The following tests were performed on both welded and non-welded specimens at 620°C (all welded specimens were tested in the direction transverse to the weld):

- Uniaxial constant displacement tensile tests
- Constant tensile load uniaxial creep tests at a variety of different nominal stress levels. Notched specimen creep testing was also performed in order to obtain the triaxial stress behavior of the material.
- Uniaxial fatigue tests at a variety of different nominal (maximum) tensile stress levels. The cycles had a trapezoidal (1-1-1-1) form with a frequency of 0.25 Hz and a stress ratio of ≈0 (i.e. 1sec ramp up/1sec dwell at max. load/1sec ramp down/1sec dwell at min. load -as can be seen in Figure 6).

The aim of these tests was to determine the required material properties for subsequent finite element (FE) modeling and life prediction.

2.1. Test results
Consistent with tests are different temperatures, the tensile tests resulted in both the 0.2% proof stress and the ultimate strength of the welded specimens exceeding 90% of the values of the non-welded specimens. However, the strain to failure for the welded specimens was significantly less than that of the non-welded specimens (Table 1). The creep tests also showed noticeably lower total strain to failure for the welded specimens than the non-welded specimens, the time to failure was also markedly less for the welded specimens. The fatigue tests resulted in lower failure times for the welded specimens than the corresponding non-welded values for any given nominal stress.

In conclusion, in common with other nickel superalloys, welded IN718 exhibits varied and complex microstructures in the fusion zone and in the heat-affected zone (HAZ). The weld region and the HAZ exhibit slightly lower tensile strength and significantly lower ductility than the parent material. Therefore, although welded IN718 exhibits comparatively little loss of tensile strength, its creep and high temperature fatigue properties are severely decreased [4].
2.2. Weld material property determination
The mechanical properties and stress-strain relationships of the IN718 welds were obtained from the testing mentioned above by calculating the difference in strain of non-welded and cross-welded specimen tests over the gauge length, and determining what the properties of the weld must be in order to give the measured test results. The calculated weld material nominal stress-strain curve at 620°C is shown in Figure 1. The engineering uniaxial tensile properties are given in Table 1. As expected, the 0.2% proof stress calculated for the weld material is lower than that obtained for both the non-welded and welded specimen tests since the weld region is only a small proportion of the welded test specimen gauge length and its properties cause the difference between the non-welded and welded specimen results. FE verification of the material properties was conducted by modeling the uniaxial tensile and creep tests to check the accuracy of the material properties assigned to the weld region. Very good agreement was obtained.

![Figure 1. Nominal stress-strain curves for heat-treated IN718 at 620°C.](image)

![Table 1. Uniaxial tensile properties of heat-treated IN718 at 620°C.](table)

|                  | 0.2% Proof stress (MPa) | Ultimate strength (MPa) | Young’s modulus (GPa) | Failure strain (%) |
|------------------|-------------------------|-------------------------|-----------------------|-------------------|
| Non-welded       | 992                     | 1163                    | 166                   | 21.8              |
| Welded (test)    | 920                     | 1064                    | 165                   | 5.7               |
| Weld (calculated)| 808                     | -----                   | 148                   | -----             |

3. Finite element analysis and life assessment of the structure

3.1. Model setup

![Figure 2. FE mesh of one-spoke section showing the weld and the boundary and loading conditions.](image)
A one-spoke (30°) section of the generic spoke structure was modeled, with a weld positioned in the blend between the spoke and the inner ring, in order to demonstrate the lifing methodology. A 3D solid ABAQUS FE mesh consisting of 20804 quadratic tetrahedron (C3D10) elements and 40587 nodes was generated. The mesh was refined in the regions of high stress that were identified after an initial analysis had been run (Figure 2). A cylindrical coordinate system with the origin at the centre of the complete structure was employed in order to conveniently define the cyclic symmetry along the edge surfaces of the one-spoke section. These surfaces were constrained in the circumferential (T) direction. The front-facing surfaces were constrained in all directions. Load was applied in the negative direction of the axis of rotation of the cylindrical coordinate system (-Z) to the nodes on the front surface of the spoke (Figure 2). The material properties of both parent (non-welded) and weld IN718 metal were obtained from the testing mentioned above. The weld properties were assumed to be uniformly distributed and isotropic, the HAZ was not considered as a separate region due to its small size and the difficulty in obtaining its properties. Two types of FE analysis were performed: a constant load creep analysis at 620°C and a fatigue analysis at 620°C.

3.2. Creep analysis

3.2.1. Procedure and life assessment method. The creep FE analysis was conducted in two steps. Firstly, the load was applied gradually during a nonlinear elastic-plastic static step. It should be noted that global yielding did not occur and plasticity was only included in order to produce a suitably high stress state to cause failure within a reasonable time frame. A nonlinear visco (transient, quasi-static) plastic step followed the loading step, for which the load was held constant. A Kachanov-type continuum damage mechanics approach was used for the creep law and life prediction since it was shown to give more accurate failure times and creep strain curves for the material test data. The following constitutive equations were used [5]:

\[
\dot{\epsilon}_y^c = \frac{3}{2} A \left( \frac{\sigma_{eq}}{1 - \omega} \right)^n S_k^m \\
\sigma_{eq} = \sigma_1 + (1 - \alpha)\sigma_r \\
\dot{\omega} = \frac{B\sigma_{eq}^2}{(1 - \omega)^3} t^m
\]

where \(\sigma_{eq}\), \(\sigma_1\), and \(\sigma_r\) are the equivalent, maximum principal and rupture stresses, respectively. \(S_k\) are the deviatoric stress components. \(\omega\) is a state variable that describes creep damage and varies from 0 (initially no damage) to 1 (failure). At time, \(t = 0\), \(\omega = 0\) and creep strain, \(\epsilon_y^c = 0\). A, \(n\), \(m\), \(B\), \(\chi\), \(\phi\) and \(\alpha\) are material constants determined from the creep tests, the values are given in Table 2.

| Table 2. Creep damage constants of IN718 at 620°C, based on units of stress in MPa and time in hr. |
|---|---|---|---|---|
| Parent (non-weld) | 2.037E-61 | 19.300 | 0.0 | 4.322E-47 | 14.728 | 12.0 | 0.1 |
| Weld | 5.260E-56 | 17.984 | 0.0 | 2.623E-50 | 16.367 | 4.0 | 0.2 |

3.2.2. Creep analysis results. Below are the results from creep FE analyses with and without weld for an applied load of 870kN.

A large amount of stress relaxation occurred during the creep step (Figure 3). The welded material was unable to support as high a stress as the non-welded material and relaxed at a quicker rate initially before steadying at a lower rate. The highest stress occurred in and around the blend between the spoke and the inner ring (Figure 3). This is also the site of the weld. The peak local creep strain was greater in the weld, but not in the region of failure, where the highest stresses caused the most creep damage (Figure 4). Failure of the non-welded case was deemed to have occurred after 137hr in the blend of the spoke-inner ring, where the weld would have been (Figure 4). Failure of the welded case occurred after 365hr on the parent side (inner ring) of the weld-parent interface. The life of the welded case is increased due to the greater stress relaxation of the weld, which causes the failure location to shift into an area that experiences lower stress than the failure location of the non-welded case.
It should be noted that the non-welded case uses properties obtained from wrought material, but this geometry cannot be manufactured without casting or welding. Also, the peak creep strain is very high in the weld and this may cause failure before the creep damage parameter indicates. Failure time determined by the time taken for maximum principal strain to reach 0.1 would give a non-welded life of 53hr and a welded life of 17hr. The failure locations for this criterion are in the lower part of the blend for the non-welded case and in the upper part of the side of the blend (in the weld) for the welded case (Figure 5).

**Figure 3.** Rupture stress: (a) non-welded case immediately after loading, (b) Final state non-welded, (c) Final state welded case.

**Figure 4.** Damage, close-up of failure positions (in red) (a) non-welded case, (b) welded case.

**Figure 5.** 0.1 maximum principal strain after (a) 53hr non-welded case, (b) 17hr welded.
3.3. Fatigue analysis

3.3.1. Procedure and life assessment method. A strain-based parameter lifting method that accounts for mean stress was chosen as in [6]. The Smith, Watson and Topper (SWT) strain range parameter was calculated for each point during the analysis using:

$$\left( \frac{\sigma_{\text{max}} \Delta \varepsilon}{E} \right)^{\frac{1}{2}}$$

where $\sigma_{\text{max}}$ is the peak stress, $\Delta \varepsilon$ is the total strain range within a cycle and $E$ is Young’s modulus. This formula is the strain equivalent to the effective stress presented by Smith, Watson and Topper [7]. This SWT parameter correlates well with cycles to failure using the test data obtained. The fatigue tests were modeled so that peak SWT values could be determined. FE-calculated values averaged over the gauge length gave good agreement with values calculated using test measurements. Therefore, an FE analysis of a structure can be used to calculate the peak SWT value and the corresponding life can be predicted by correlating with the fatigue test data.

The mesh, weld position, boundary conditions, loading position and direction were the same as those used in the creep analysis. The fatigue loading was the same as that used for the material testing (trapezoidal (1-1-1-1) form with a load frequency of 0.25 Hz and a stress ratio of $\approx 0$). The analysis was nonlinear visco (transient, quasi-static) plastic so as to include the effect of creep, the accumulation of which was accounted for during the fatigue cycles using Norton’s creep law:

$$\dot{\varepsilon}^{c} = A \sigma^{n}$$

where $A$ and $n$ are given in Table 2.

Two steps were performed, each equivalent to one cycle; all results were taken from the second step, which is a more stable representation of subsequent cycles than the initial loading cycle. The values of maximum stress, strain range and Young’s modulus, taken from the FE models, were converted to SWT strain range and read into the specimen fatigue test lifting curve.

3.3.2. Fatigue analysis results. Below are the results from fatigue FE analyses with and without weld for an applied load of 250kN.

Since there is only a short period of hold during each fatigue cycle, little creep and subsequent stress relaxation occurs. Plastic yielding is present during the first cycle and then this stabilizes due to material hardening. The welded material yields more and is unable to support as high a stress as the non-welded material due to its lower yield stress (Figure 6 and Figure 7), therefore it also strains more.

![Figure 6](image_url)

**Figure 6.** (a) von Mises stress history, (b) maximum principal strain history at peak position.
The predicted location of failure occurs in the blend region between the spoke and the inner ring in both cases, shown by the highest value of SWT in Figure 8. This is also the site of the weld. The value of SWT is slightly higher (<1% increase) for the welded case since the slightly higher strain range is countered by the lower peak stress and Young’s modulus. When the predicted values of SWT are compared with those from the test specimens, a life prediction of 108300 cycles is obtained for the non-welded case, while just 1260 cycles for the welded case (Figure 9). This marked reduction of life is expected due to the depleted high temperature fatigue properties of the welded material as discussed previously. To give an expected life of approximately 10000 cycles for the welded case, the applied load would need to be reduced by 8% to 230kN. To give a similar life for the non-welded case (using wrought material properties), a load of 280kN could be applied, which is an increase of 12% from the original load, and over 20% higher than the load for the equivalent welded case.

Figure 7. von Mises stress distribution at maximum load (a) non-welded case, (b) welded.

Figure 8. SWT distribution (a) non-welded case, (b) welded.
4. Conclusion
Although welded IN718 exhibits comparatively little loss of tensile strength, its creep and high temperature fatigue properties are severely decreased. The depleted high temperature fatigue properties of the welded IN718 material have a negative effect on the predicted high temperature fatigue life of the structure examined here. The effect of the weld on the life of the structure under constant loading at high temperature was found to be more difficult to quantify due to significant stress relaxation. The predicted failure location was affected by the weld in the constant load case but not in the fatigue load case. Failure would be expected to occur in the region of greatest stress (at the blend where the spoke meets the inner ring) but due to significant stress relaxation in the welded case, the failure location shifts to the parent side (inner ring) of the weld-parent interface.

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