The Design of Bellows Expansion Joints for High Temperature Application

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Abstract

The life assessment of cold-worked tubular bellows units is discussed with particular reference to Incoloy 800 material. Results of tests to determine mechanical properties and failure criteria are given while a simplified non-linear analysis method is applied to the bellows. From these results a design creep fatigue curve for cold-worked Incoloy 800 bellows at 650°C is constructed. This curve requires only a knowledge of the elastically calculated behaviour of a bellows in service and implies that the effect of cold work may improve the life expectancy beyond that of a similar annealed unit.

1. Introduction

Large differential movements between tubular components are frequently accommodated by the use of tubular bellows expansion joints. In applications where these components are subject to long term elevated temperature operation under cyclic loading conditions the design life assessment becomes complex. Present design codes reflect this difficulty by either excluding any assessment of the damaging effects of creep strains due to stress relaxation EJMA[1], AD-M[2], or by requiring that representative life tests be carried out on several units satisfying similitude requirements ASME [3]. The former approach is unacceptable while the latter is undesirable. There is thus a strong incentive to develop an alternative design philosophy for high temperature nuclear applications.

A particular aspect for consideration is the implication of cold working of the bellows material during forming. The level of cold work is generally high (20% typically) and is considered beneficial to the fatigue properties while being detrimental to the creep-fatigue properties. For this reason ASME [3] recommend that bellows units designed for elevated temperature applications are heat treated subsequent to forming in order to recover the ductility lost by cold working. Since this introduces an additional process into the manufacturing route and may also lead to a final forming process requirement it is worthwhile establishing the implications of utilising bellows units which have not been heat treated in elevated temperature applications.

The object of this paper is to describe the development of fatigue and creep-fatigue design curves for cold worked Incoloy 800 bellows units operating at temperatures up to 650°C in an attempt to give greater confidence to the use of tubular bellows expansion joints in high temperature nuclear plant applications.

2. Mechanical Properties

In order to understand the mechanical behaviour of a bellows unit it is necessary to determine the mechanical properties of the component material. These properties are influenced by both the manufacturing and service histories. Mechanical tests to determine these properties must therefore reflect these conditions as closely as possible. If appropriate test results are obtained it is possible to estimate the steady cyclic stress-strain response at the critical sections of a bellows unit from which an assessment of the cyclic life can be made.

A particular application being discussed in this paper relates to double-ply bellows of 600mm diameter with a convolution depth of 14mm and ply thickness of 0.4mm. By sectioning through the convolutions of such a unit and carrying out hardness measurements it was found that the hardness varied both around the section and through the section thickness with the maxima occurring at the convolution crests and at the ply surfaces.

In order to evaluate the degree of cold working that the unit had been subjected to a number of strip specimens from the parent sheet material were progressively extended and hardness measurements taken after each increment of strain. The results are summarised in Fig.1 which shows the variation of hardness with tensile elongation. Comparing this figure with the results of hardness measurements of the bellows convolutions indicated that the degree of cold work in the bellows unit was about 20%.

To establish the stability of the properties at elevated temperature several strips were pre-strained by 20% and aged in vacuo at 650°C for periods up to 3000 hours. After ageing the hardness was measured and compared with the original as-received and cold worked values. Some softening was evident with a minimum hardness value of 190 VPN after 3000 hours. The affect however appeared to have saturated after about 100 hours and it is not anticipated that any further softening would occur in a reactor lifetime of 30 years.

The stress-strain response of 20% cold worked material was evaluated by tensile test of prestrained strips and is compared with the response of the parent material in Fig.1. An additional curve is included in the figure which has been obtained by interpolation with respect to the change in hardness observed after ageing. The resulting curve is considered a best estimate of the material response under slow cycling and dwell conditions at 650°C. A best fit to this curve has been obtained assuming the Ramberg-Osgood relation

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{E_p}\right)^M \qquad (1)$$

Pre-strained strip specimens were also tested under constant tensile load conditions to determine the time dependent behaviour and strength at 650°C. A best fit to the minimum creep rates was obtained by assuming a Norton Law form

$$\dot{\varepsilon}_{cr} = A\sigma^n \qquad (2)$$

It was observed that the stress index obtained was very similar to that derived for the as-received material.

In addition to the constant load creep tests a number of prestrained strips were tested under constant displacement conditions. The specimens were extended to 0.5% strain and held for 100 hours. By curve fitting a description of the form

$$\dot{\varepsilon}_{cr} = A\sigma^{n}t^{m} \qquad (3)$$

was found to describe the data reasonably well. However, the comparison between cold-worked and as-received behaviour was not good in this case owing to the greatly differing transient behaviour.

3. Structural Analysis

The elastic behaviour of tubular bellows expansion joints is well understood and simple formulae for the calculation of the maximum principal stresses in the convolutions are given by EJMA [1]. The inelastic behaviour is however complicated by the local enhancement of instantaneous and time dependent inelastic strains around the crests of the convolutions. The cyclic stress-strain response at the surface of a convolution crest during cyclic compression of a bellows unit with a 1000 hour dwell has been computed using a finite element technique and the result is shown in Fig. 2. This example shows how the elastically calculated strain range underestimates the total strain range while the creep strain accumulated during stress relaxation is enhanced by elastic follow-up within the convolutions. This implies that either full inelastic analysis is required to determine the cyclic response accurately or that factors must be applied to elastic calculations to bound this response.

It has been shown by Lee [4] how the cyclic response may be bounded from the results of elastic analysis and a knowledge of the yield and creep properties of the material. An approximate analytical method has been derived by Nguyen and Lee [5] for bounding the problem utilising the Ramberg-Osgood and Norton Laws to describe the constitutive behaviour. This demonstrates the interaction between the plastic and creep parts of the cycle through the indices m and n from eq.1 and eq. 2.

From the materials tests on cold-worked Incoloy 800 mentioned above, it was found that these two governing indices, m and n, were approximately equal at a value of about 8. This makes the bounding construction of the local stress-strain response simpler and reduces to a single enhancement factor given by

$$Z = \frac{n+2}{3} \qquad - (4)$$

This corresponds to the principle adopted by PRNFDC [6] for the assessment of pressure vessels where no explicit account is taken of the difference in plastic and creep enhancements.

The construction of the cyclic stress-strain response at the critical point on a convolution crest is exemplified in Fig.3. The process consists of evaluating the elastic response utilising the equations of EJMA [1] to give the point A on Fig.3. The enhancement factor, defines the slope of the line AB. The intercept of this line with the steady cyclic stress-strain curve, B' gives the initial stress-strain response. By choosing a lower bound value for the relaxation stress, σ_{rH} corresponding to the length of the creep dwell the point B'' is found to bound the elastic follow-up during the dwell. The unloading path utilises a similar methodology by first obtaining point C as that due to elastic unloading from B''. The final unloaded stress-strain point D is obtained from the intercept of OC with the stress-strain curve having its origin at the intersection of the strain axis by the line B''C. The process is repeated for the loading path from D to obtain B'_2. The steady cyclic response has then been bounded by the loop B_2'B"DB_2'. At this stage the total strain range, $\Delta\varepsilon$ and the creep strain per cycle, $\Delta\varepsilon_{cr}$ can be obtained directly as indicated in Fig. 3.

4. Life Assessment

From continuous cycling considerations the life of a cold-worked bellows is potentially greater than that of a similar unit that has been heat treated after forming. However, when utilising elastically calculated stresses to assess the fatigue life of a bellows unit it is important to recognise the strain enhancement that occurs at the convolution crests. It is expected therefore that the elastic fatigue failure curve will fall below the corresponding material curve when strain ranges imply alternating plasticity. This effect is demonstrated in Fig.4 which compares the mean failure curve for austenitic stainless steel from ASME [7] with the bellows failure curve from EJMA [1] and unpublished data from UK bellows manufacturers. With the exception of the very low cycle regime it is seen that the EJMA failure curve adequately bounds the data. Applying suitable design factors such as the 2 on strain, 20 on cycles adopted by ASME [7] would ensure adequate confidence in the design of bellows units subject to fatigue conditions in nuclear installations.

At elevated temperatures however the introduction of creep strain during slow cycling or dwell conditions can dramatically reduce the cyclic life of a bellows unit. Under these conditions it is not clear whether prior cold working affects the life of a unit in a beneficial or deleterious way. The issue has been discussed in relation to general nuclear applications by Moen and Smith [8] who indicate that for significant levels of cold work substantiation of a component is the responsibility of the designer and that design codes are likely to be non-conservative in these cases. It is emphasised that the ductility of cold-worked material will be lower than its annealed counterpart.

From the tensile creep tests described in section 2 the elongation at failure was obtained for as-received and cold-worked material. These data have been plotted against the minimum creep rate in each test. From the results it is observed that the ductility tends to fall with decreasing strain rate and that at the lowest rates the cold-worked material exhibits 15% ductility, about half the as-received ductility value. For design purposes, observing that the trend is for the ductility to continue falling with decreasing strain rates, a value of 5% has been assumed for the cold-worked material.

By utilising the method described in section 3, the creep strain per cycle has been evaluated for a range of elastically calculated strain ranges, $\Delta\varepsilon_e$ .For this exercise a relaxation stress, σ_{rH} of 50 N/mm² was assumed from the observation of relaxation data and the derived creep laws. By assuming that all creep strain accumulated during a cycle, $\Delta\varepsilon_c$ is damaging against the ductility of 5% then the allowable number of cycles for ductility exhaustion is readily obtained, Nc. Utilising the estimated strain range, $\Delta\varepsilon$ with an appropriate design fatigue curve such as figure T-1420 of ASME [9] the allowable number of cycles for fatigue failure is obtained, Nf. It has then been assumed that a linear damage summation rule applies,i.e

$$\frac{Nd}{Nf} + \frac{Nd}{Nc} = 1 \qquad - (5)$$

Solving eq.5 for Nd for a range of elastic strain ranges $\Delta\varepsilon_e$ gave the design creep-fatigue curve shown in Fig.4. The design creep-fatigue curve for Incoloy 800H material published by ASME [9] is included for comparison. It can be seen from this figure that with the exception of the very low cycle regime the ASME design curve bounds the estimated result for cold-worked bellows. This is primarily due to the increased elastic stress/strain range in the cold-worked material which results in elastic shakedown at higher nominal strain ranges. The shakedown boundary is a point below which very little creep damage can occur during cyclic loading and hence influences the creep-fatigue design curve.

The resultant design curve is intended to be used for bellows manufactured from the Incoloy 800 material examined in the test programme at temperatures up to 650°C subject to cyclic displacements with dwells up to several thousand hours. The strain ranges in a bellows unit are calculated elastically using the relations given by EJMA [1]. The estimated total strain ranges that the units undergo are indicated in Fig.4 by the dashed line and indicates the degree of strain enhancement anticipated in the convolution crests.

The method of life assessment for cold-worked bellows described here is the subject of a continuing test and analytical programme the next phase of which includes long term testing of bellows units under creep-fatigue conditions. This is intended to validate many of the assumptions that have been made in developing the design curve as well as demonstrating the apparent benefit of cold-working in the creep dominated regime.

5. Conclusion

Consideration of cold work within bellows units indicates that although the ductility of the material at elevated temperature falls below that of its annealed counterpart, the effect is offset under creep-fatigue conditions by increased elastic stress ranges. The construction of a design creep-fatigue curve for Incoloy 800 bellows with approximately 20% cold work implies a general improvement in endurance compared with annealed material behaviour. Under pure fatigue conditions a similar observation may be apparent but general test results on bellows units suggest consistent behaviour with annealed material fatigue performance. A test and analytical programme is continuing with the aim of validating the methods and observations made in this work.

6. Acknowledgements

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6. References

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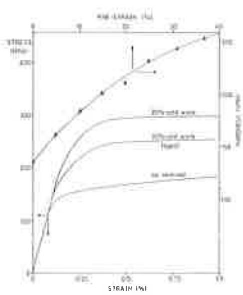
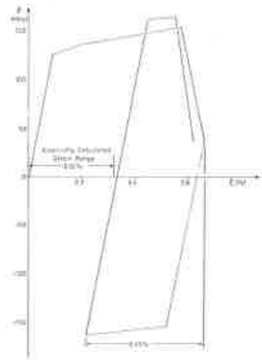
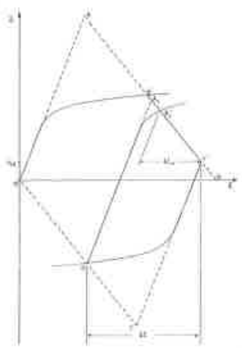


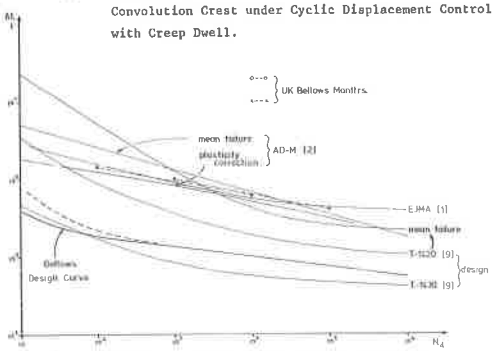
1. Variation of Hardness with Pre-strain and the Stress-Strain Characteristic for As-received and Cold-worked Incoloy 800 at 650°C.



2. Computed Cyclic Stress-Strain Response in Bellows Convolution Crest under Cyclic Displacement Control with Creep Dwell.



3. Simplified Method of Construction for Cyclic Stress-Strain Response in Bellows Convolution Crests.



4. Fatigue and Creep-Fatigue Curves for Incoloy 800 Cold-worked Bellows at 650°C.