Non-Proportional Behaviour of a Nickel-Based Superalloy & Characterisation of the Additional Hardening Response by a Modified Cyclic Hardening Curve

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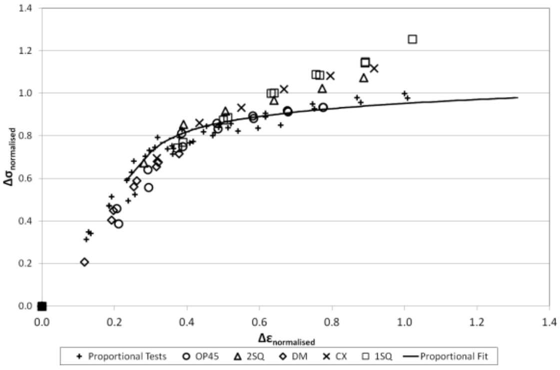
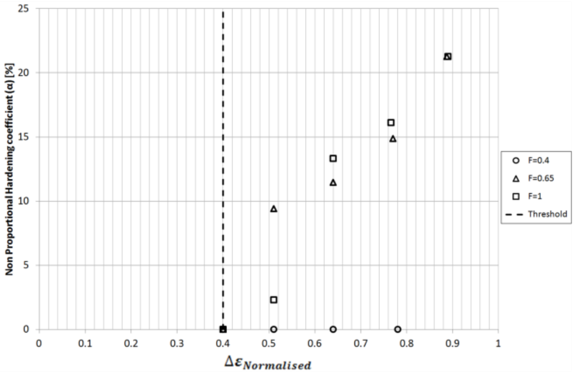
INTRODUCTION

A study was carried out where tension-torsion deformation strain-controlled tests were completed at Swansea University, to characterise the non-proportional hardening response of a nickel-based superalloy at different strain ranges. The data generated was used to assess the validity of a non-proportional cyclic hardening curve correction proposed by Socie and Marquis to represent the material's hardening response. This modification involves the linear translation of the proportional cyclic strain hardening curve to represent the additional hardening response.

RESULTS AND DISCUSSION

The magnitude of non-proportional hardening was found to be dependent on the applied strain range. Different strain paths at the same degree of non-proportionality exhibit the same hardening response.





A threshold degree of non-proportionality exists at which there is no observable non-proportional hardening effect.

CONCLUSION

A linear modification to the standard cyclic hardening curve does not capture the variation in non-proportional hardening at different strain ranges nor does it capture the absence of non-proportional hardening at an intermediary degree of non-proportionality.

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ABSTRACT. *Multi-axial deformation strain-controlled testing was completed at Swansea University, to characterise the non-proportional hardening response of a nickel-based superalloy. The data was used to assess the validity of a non-proportional cyclic hardening curve correction, proposed by Socie & Marquis [1] to represent the hardening response of this alloy. The cyclic hardening response was characterised by the application of axial and torsional strains in a servo-hydraulic tension-torsion test machine, utilising an incremental step method. A square strain path, equivalent to a fully out-of-phase loading, was found to exhibit additional hardening at moderate peak applied strains compared to the proportional in-phase case. This additional hardening was not observed at low strain levels or at a test condition applying a lower level of non-proportionality in the applied strain path. Furthermore, at low plastic strain levels, no significant additional hardening was observed.*

INTRODUCTION

Nickel-based superalloys are widely used in rotating aero engine components, due to their excellent strength, corrosion and fatigue resistant properties across a range of cold and hot operating temperatures. These components are subjected to varying thermal and centrifugal stresses throughout a typical flight cycle generating a multi-axial stress state and this impacts the low-cycle fatigue life. It has been well reported in the literature that non-proportional loading is more damaging than proportional loading under strain controlled conditions attributed to additional cyclic hardening which leads to a reduction in low cycle fatigue life [1-5]. The intention of this article is to capture the non-proportional cyclic hardening response of a nickel-based superalloy at room temperature, subject to strain-controlled tension-torsion deformation testing at Swansea University, at different strain ranges. The data generated was used to assess the validity of a non-proportional cyclic hardening curve correction proposed by Socie and Marquis [1] to represent the material's hardening response.

Non-proportional Cyclic Hardening

Non-proportional is the term used to describe loading paths where the principal strain axes rotate during cyclic loading. Out-of-phase loading is a specific case of non-proportional loading. It denotes cyclic loading histories involving sinusoidal or trapezoidal waveforms where a phase difference exists between the applied loads. This type of non-proportional loading can be easily replicated in the laboratory by the independent application of axial and torsional loads on a thin-walled cylindrical test specimen.

The additional non-proportional hardening response can be characterised by a material dependent non-proportional hardening coefficient (α) introduced by Socie & Marquis [1]. This coefficient represents the maximum degree of non-proportional hardening achieved by a tension-torsion 90° out-of-phase loading compared to the equivalent in-phase loading at the same equivalent strain amplitude. This is defined at high plastic strains, in the flat portion of the stress-strain curve (Figure 1).

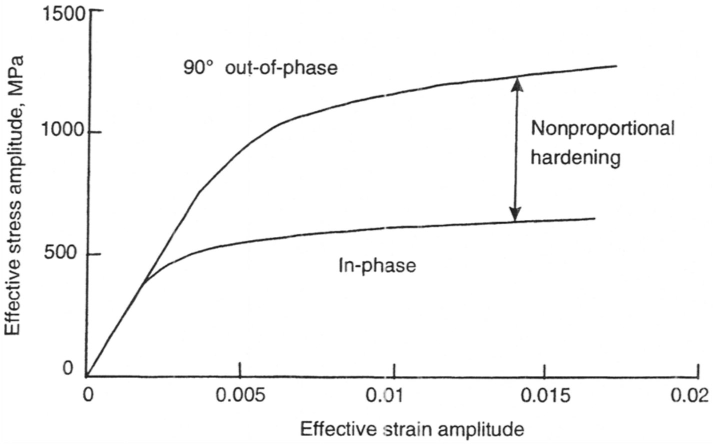

Figure 1. Typical Cyclic Stress-Strain Curve for Proportional and Non-proportional Loading [1]

Socie & Marquis [1] stated that experiments showed that this additional non-proportional cyclic hardening (K'_{NP}) could be modelled by an increase in the cyclic strength coefficient. Equation (1) and (2) adapts the Ramberg-Osgood representation of the standard (proportional) cyclic hardening curve to account for the additional hardening.

$$\overline{\sigma} = K'_{NP}\left(\overline{\varepsilon}_p\right)^{n'} \tag{1}$$

$$K'_{NP} = K'(1 + \alpha F) \tag{2}$$

where $\bar{\sigma}$ and $\bar{\varepsilon}_p$ are the effective stress and plastic strain respectively, and K' and n' are the Ramberg-Osgood cyclic strength and strain hardening coefficients respectively. These coefficients can be captured from uniaxial loading [1]. The load path dependency factor F defines the degree of non-proportional loading in the range zero to one: zero denotes a fully proportional cycle, whilst one represents a cycle involving the maximum degree of non-proportionality. Hence, for any given non-proportional loading path the additional cyclic hardening response is characterised, by this modification, as a linear shift in the cyclic strain hardening curve.

Load Path Dependency

The load path dependency factor is obtained by plotting the full strain path onto effective axial-torsional strain space (Figure 2). The major to minor axis ratio of an ellipse enclosing the strain path locus defines the factor, as indicated by Equation (1). A fully proportional strain path will plot out a straight line, whilst any non-proportionality in the strain path will open this out.

$$F = b/a \tag{1}$$

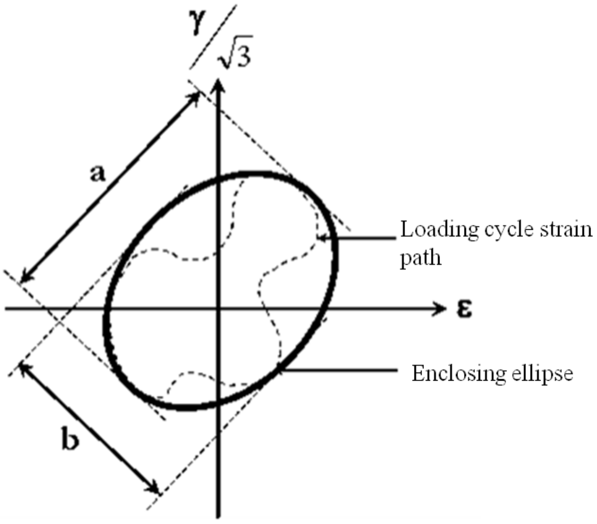

Figure 2. Determination of the Load Path Dependency Factor [2]

This paper will apply this modification to the tension-torsion test data generated at Swansea University, and comment on the application's success.

EXPERIMENTAL METHODS

A servo-hydraulic (100 kN, 200 Nm capacity) test machine was used to conduct a series of multi-axial (tension-torsion) strain-controlled deformation tests at Swansea University. It utilises a separate axial and torsional actuator aligned in the axial direction to enable the simultaneous application of axial and torsional loads both in a proportional and non-proportional manner. Thin-walled hollow cylindrical test specimens were used for the strain-controlled deformation test programme. Nominal dimensions were 8 mm and 10 mm for the inside and outside diameters respectively. The gauge length was 25 mm. The specimen was internally reamed and honed, and externally polished across the gauge length to a consistent surface finish. Conical ends to the specimen ensure a uniform circumferential mechanical interface and enable the firm application of torsional loads across a fully reversed load cycle.

A total of 14 strain controlled incremental deformation step tests were carried out to determine the uniaxial and multi-axial deformation behaviour of the nickel-based superalloy. All tests were at room temperature. Figure 3 displays the applied tension-torsion strain paths, where ε_{xx} and γ_{xy} are the axial and shear strains respectively. The 8 strain paths exploited for this programme are split into 3 types of proportional loading and the remaining 5 types of non-proportional loading. The proportional tests are defined as pure uniaxial (UX), pure torsion (TS) and in-phase (IP). The non-proportional tests are identified as 45º out-of-phase (OP45), 2 square out-of-phase (2SQ), 90º diamond out-of-phase (DM), cross out-of-phase (CX) and 90º square out-of-phase (1SQ). The majority of test conditions were repeated to capture the inherent variation in material response.

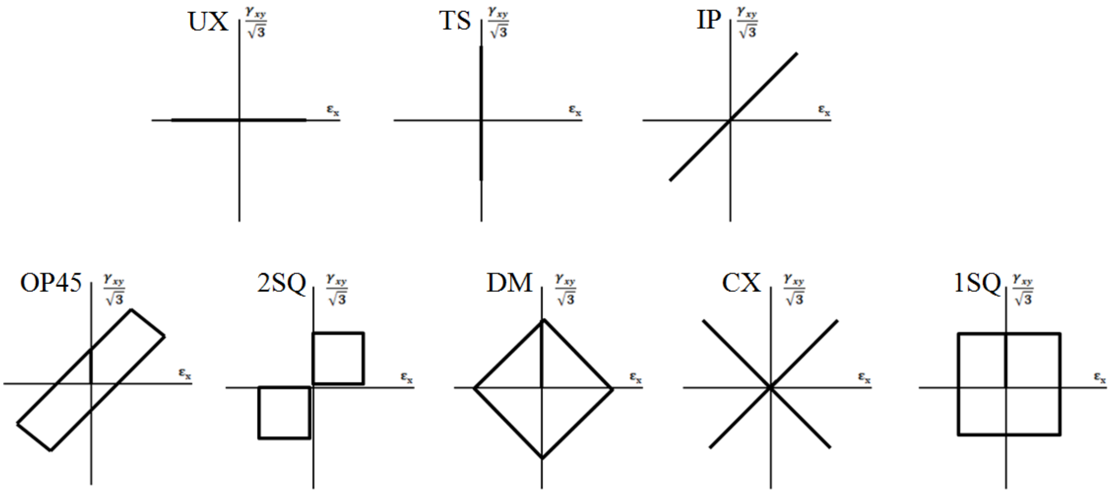

Figure 3. Tension-torsion Strain Paths

The load path dependency factor was determined for each tested strain paths and is shown in Table 1.

Table 1. Load Path Dependency Factors obtained from Test Data

Strain Path	**F**
UX	0.04
TS	0.04
IP	0.04
OP45	0.40
2SQ	0.65
DM	1.00
CX	1.00
1SQ	1.00

To generate the cyclic stress-strain curve for the proportional and non-proportional load paths an incremental step method was applied [6]. Each specimen is subjected to linearly increasing strain amplitudes, where each is repeated for 50 cycles before increasing to the next strain amplitude level (Figure 4). A consistent strain rate of 0.50%/sec was used for all tests. This process was repeated until the maximum achievable strain amplitude was reached or specimen failure, whichever happened first. For each amplitude the effective axial and torsional strains, where applicable, were equal.

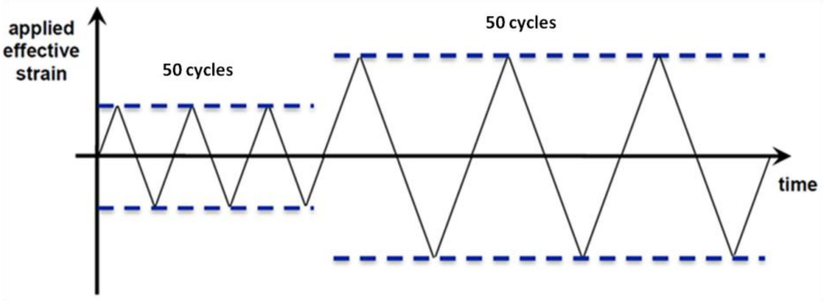

Figure 4. Incremental Step Method

The resulting stable hysteresis loops provide the cyclic-stress-strain curve for the load path.

RESULTS & DISCUSSION

Figure 5 shows the cyclic stress-strain response obtained across the proportional and non-proportional strain paths. The stress and strain range axes have been normalised against the peak stress and strain range achieved by the proportional tests. The CX and 1SQ strain paths display an additional hardening effect at a higher plastic strain range than proportional equivalents tests. Both these strain paths have the same degree of non-proportionality. The DM strain path did not achieve the same high levels of strain range due to the premature failure of the specimen.

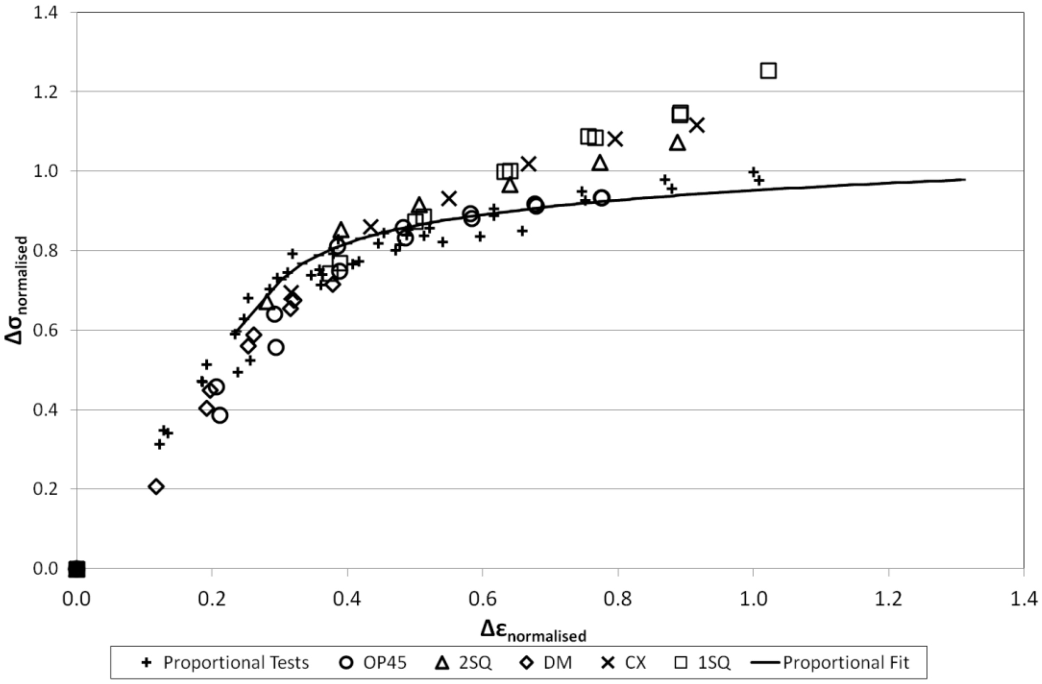

Figure 5. Cyclic Stress-strain Response of the Tested Strain Paths

The magnitude of this hardening is strongly dependent on the microstructure and hardness level, for example, involving the interactions of different slip systems and dislocations in the material during plastic deformation [6]. Therefore, it has been suggested by Fatemi [3] and Bonacuse [4], that many slip systems are activated during out-of-phase loadings, increasing the interaction of the dislocations and increases the cyclic hardening of the material. To assess the validity of the generated pseudo-stabilised stress-strain curves by the incremental step method, a 1SQ was cycled directly at the peak strain amplitude until failure. The resultant data point in Figure 5 is the maximum stress range achieved for this strain path and it follows the observed hardening trend.

The Socie and Marquis Ramberg-Osgood modification applies a linear offset to the proportional cyclic stress-strain curve to account for the additional non-proportional hardening. Figure 6 shows the level of additional hardening observed for non-proportional strain paths at the different applied strain amplitudes. The different legends represent an average across the tests hosting these load path dependency factors. It is clear a linear shift in the stress response does not match the observed non-proportional hardening response. The level of additional hardening is instead dependent on the applied strain range. This variation is also seen in the 2SQ ($F = 0.65$) strain path test.

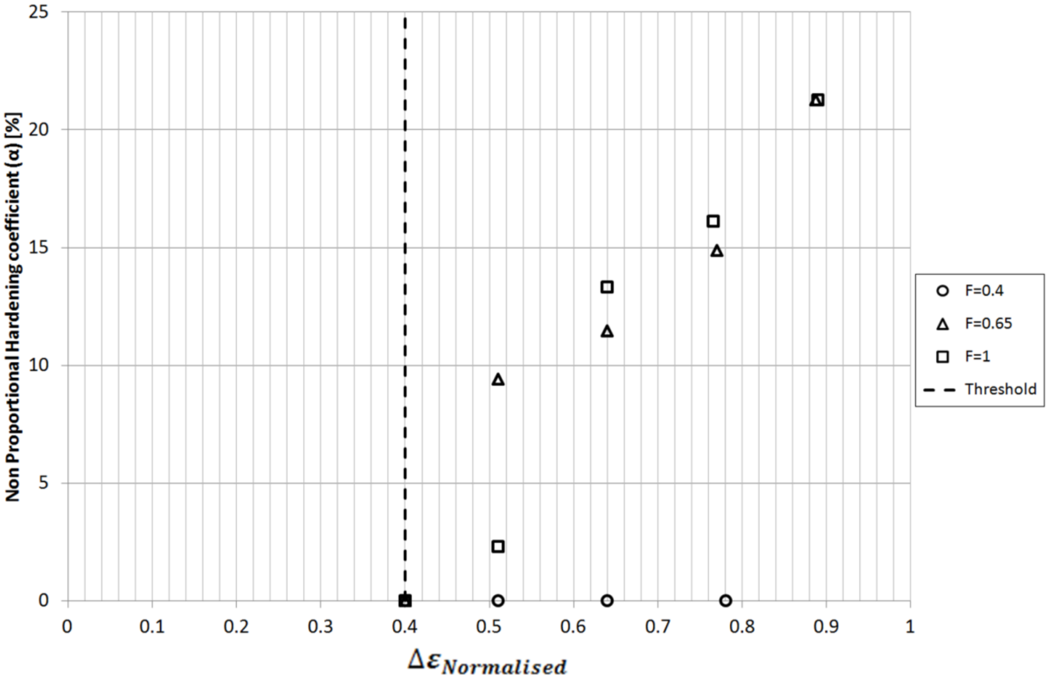

Figure 6. Additional Hardening as a Function of Strain Range

The OP45 ($F = 0.40$) strain path gave no additional cyclic hardening for all applied strain ranges. This indicates a threshold degree of non-proportionality may exist to the additional hardening effect.

CONCLUSIONS

A variety of strain controlled multiaxial low cycle deformation tests of a nickel-based superalloy, and its non-proportional hardening response, have been investigated in this study. Whilst, the presence of additional cyclic hardening was an expected result from the testing, several additional relationships were observed:

1) No additional non-proportional hardening was present at low plastic strain levels.
2) A linear modification to the full standard cyclic hardening curve is insufficient to capture the non-proportional hardening effect across all strain ranges.
3) No additional non-proportional hardening was observed at a load path dependency factor of 0.40.
4) The non-proportional hardening response of the nickel-based superalloy is dependent on applied strain range and a threshold load path dependency factor.

ACKNOWLEDGEMENTS

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