# SUSTAINED LOADING EFFECTS IN AUSTENITIC 316 STEEL

G. Wardle*, R. P. Birkett* and P. J. Budden+

An experimental study of sustained load failure in type 316 austenitic stainless steel was undertaken in order to clarify guidelines in the R6 defect assessment procedure on sustained loading effects. The results have shown that time-dependent failure may occur at ambient temperature if the sustained load is in excess of 65% of the plastic collapse load. The implication with respect to assessments of austenitic components using R6 is that sustained loading effects may have to be considered when the value of the parameter which measures the proximity to plastic yielding ($L_r$) is greater than 65% of the $L_r$ cut-off value on the failure assessment diagram ($L_r^{max}$). For the steel tested this indicates a value of $L_r > 1.1$.

## INTRODUCTION

It is known that time dependent crack growth can occur in steels at temperatures well below the creep range. Since crack growth under sustained loading involves plastic deformation processes, the effects are negligible below the onset of general yielding of a structure and hence can be ignored in an assessment for ratios of load to yield load less than unity. Currently R6(1) recommends that sustained loading can be neglected for loads less than 90% of the plastic collapse load. Outside these limits, time dependent plasticity effects become progressively more important with increasing load, and the effect of limited crack extension on the integrity of the structure under all possible loading conditions needs careful assessment. This paper describes results from sustained loading tests on 316 austenitic stainless steel to review advice given in R6.

* Structural Performance Department, AEA Technology, Risley, UK
+ Structural Integrity Branch, Nuclear Electric, Barnwood, UK

## EXPERIMENTAL

Compact geometry specimens (W=40mm, B=20mm) were machined from a 25mm thick plate of 316 austenitic steel. These were fatigue pre-cracked to final normalised crack lengths ($a_o/W$) of 0.5, 0.6, and 0.7, using an R-ratio of 0.1, and at a stress intensity factor less than $15\text{MPa}\sqrt{\text{m}}$. Specimens were either plain sided or 50% side grooved to a net thickness $B_N$=10mm. Tensile data were obtained to define the material flow stress $\sigma_{flow}$. All specimens were tested at ambient temperature. J-Resistance curves were determined in accordance with ESIS procedure P2-91D (2), and provided estimates of initiation toughness, $J_{0.2}$. Values of J at the first attainment of maximum load, $J_{oPmax}$, were calculated from the empirically derived relationship below, where C = 986.4 $\text{kJm}^{-2}$ for plain sided and 846.4 $\text{kJm}^{-2}$ for 50% side grooved specimens, respectively.

$$J_{0_{P\max}} = C - 938.2\left(\frac{a_0}{W}\right) \tag{1}$$

Sustained load tests provided failures for times up to approximately 100 hours (e.g. Figure 1). Load hold values, $P_h$, were a proportion of the estimated plastic collapse loads, $P_c$, determined using a Von Mises (plane strain) solution i.e.

$$P_c = 1.15 B_N W \sigma_{flow}\left[\left(2.702 + 4.599\left(\frac{a_0}{W}\right)^2\right)^{0.5} - \left(1 + 1.702\left(\frac{a_0}{W}\right)\right)\right] \tag{2}$$

Figure 2 shows test data plotted in a normalised form of ($P_h/P_c$) against test duration. Full symbols indicate failure, and the open symbols those tests which were stopped prior to failure. Figures 3 and 4 show respectively J hold data normalised with respect to initiation toughness ($J_h/J_{0.2}$) and J at the predicted onset of maximum load ($J_h/J_{oPmax}$). Data are summarised in Table 1 and indicate the minimum observed values of the above parameters which led to sustained loading failure of the specimens. Minimum values are shown bracketed in italics.

## DISCUSSION

Materials data, fracture toughness J-R and $J_{0.2}$ and tensile properties, presented in this paper have been obtained using conventional testing procedures. The use of the Von Mises plane strain collapse solution (equation 2) in an R6 assessment is also consistent with current guidelines.

Sustained loading at loads significantly below the estimated plastic collapse loads led to time-dependent failure. At levels of load-hold, $P_h$, above 65% of the plastic collapse load, $P_c$, failure may occur within a few hours. Figure 1 shows a typical example of failure curves (displacement versus time) and sustained loading failures may occur within 100 hours when all of the following criteria are met for the size of specimens tested in this programme:

$$\left(\frac{P_h}{P_c}\right) \geq 0.65 \qquad \left(\frac{J_h}{J_{0.2}}\right) \geq 0.35 \qquad \left(\frac{J_h}{J_{oP\max}}\right) \geq 0.25$$

This suggests that once general yielding is approached and ductile tearing is initiated (which is at a J level < $J_{0.2}$ for this material) then a sustained loading failure is a possibility. [NB. initiation of ductile tearing in this material as determined from stretch zone width measurements was at 0.09mm crack extension].

Comparisons with other data on 316 stainless steel

Picker et al (3) undertook sustained loading (hold-time) tests on a 316 stainless steel at 20°C using similar specimens. For the three specimens which failed in their studies these data have been re-analysed in terms of the ($P_h/P_c$) and ($J_h/J_{0.2}$) parameters. This has enabled a like comparison of data to be made (Table 2 cf Table 1) and shows that these are consistent with data presented in this paper.

## CONCLUSIONS

Results of this study on time-dependent sustained loading of fatigue pre-cracked compact geometry fracture toughness specimens taken from 316 stainless steel plate have indicated that:

(i) Time-dependent failure may occur in austenitic 316 material at ambient temperature when the following conditions are met:

- The sustained load is in excess of 65% of the plastic collapse load.
- The J value at load-hold, $J_h$, is in excess of 35% of the engineering definition of initiation of ductile tearing $J_{0.2}$.
- The J value at load-hold, $J_h$, is in excess of 25% of the value of J at the onset of plastic collapse $J_{oPmax}$..

(ii) The implication with respect to the guidelines given in R6 is that sustained loading effects may have to be considered in any assessment of austenitic steels at ambient temperature for values of $L_r > 0.65L_r^{max}$ i.e. $L_r > 1.1$.

## ACKNOWLEDGEMENTS

This work was carried out as part of the R6 programme sponsored by Nuclear Electric plc, AEA Technology, British Nuclear Fuels Ltd and Scottish Nuclear Ltd, and the paper is published with permission of AEA Technology and Nuclear Electric plc.

## REFERENCES

1. I Milne, R A Ainsworth, A R Dowling & A T Stewart "Assessment of the integrity of structures containing defects" R/H/R6 - Revision 3, May 1986.

2. ESIS P2-91D "Procedure for determining the fracture behaviour of materials" European Structural Integrity Society Publication, May 1991.

3. C Picker, A L Stott and H Cocks Internal UKAEA document, 1983.

TABLE 1 Comparison of Normalised Sustained Loading Parameters for the Different Compact Geometries Specimens of 316 Steel Tested.

| | | a/W = 0.5 | a/W = 0.6 | a/W = 0.7 |
|---|---|---|---|---|
| $(P_h/P_c)$ | NSG | ***(0.67)*** | 0.70 | 0.77 |
| | 50% SG | 0.86 | 0.80 | 0.76 |
| $(J_h/J_{0.2})$ | NSG | 0.87 | 0.94 | 0.64 |
| | 50% SG | 0.69 | 0.41 | ***(0.38)*** |
| $(J_h/J_{oPmax})$ | NSG | 0.28 | 0.38 | 0.33 |
| | 50% SG | 0.33 | ***(0.27)*** | 0.38 |

Table 2 Re-analysed Sustained Loading Data from Reference 3

| a/W | $(P_h/P_c)$ | $(J_h/J_{0.2})$ | $t_f$ (hours) |
|---|---|---|---|
| 0.534 | 0.73 | 0.677 | 55 |
| 0.551 | 0.77 | 0.694 | 52 |
| 0.555 | 0.87 | 1.555 | < 1 |

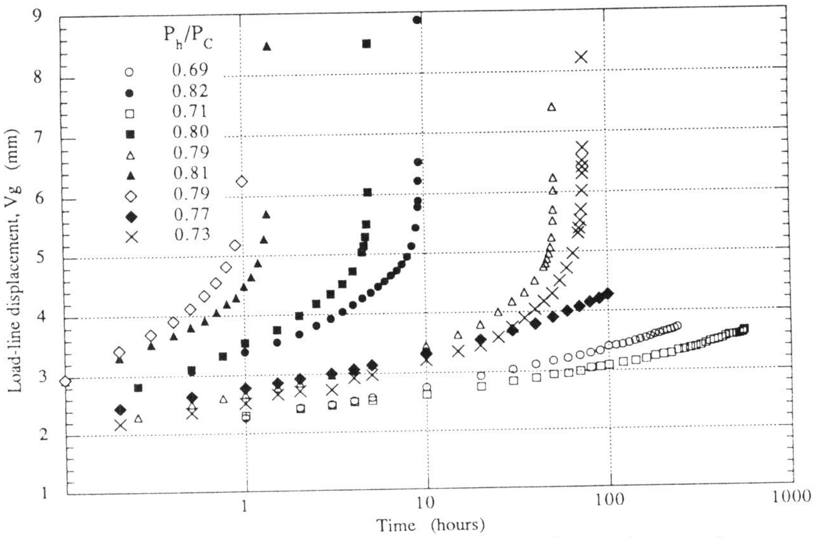

Figure 1. Load line displacement versus time plot for non-sidegrooved specimens; a/W = 0.6 (logarithmic plot)

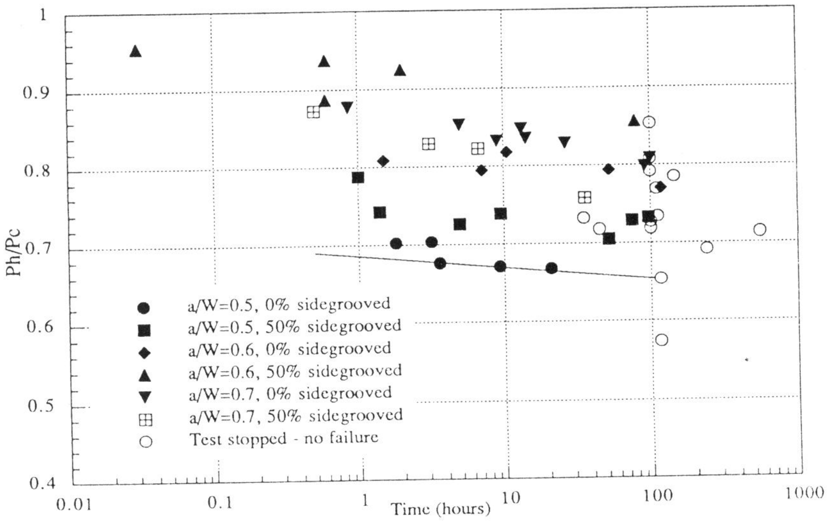

Figure 2. Load-hold test data showing holding load (normalised by the Von Mises collapse load) as a function of time to failure

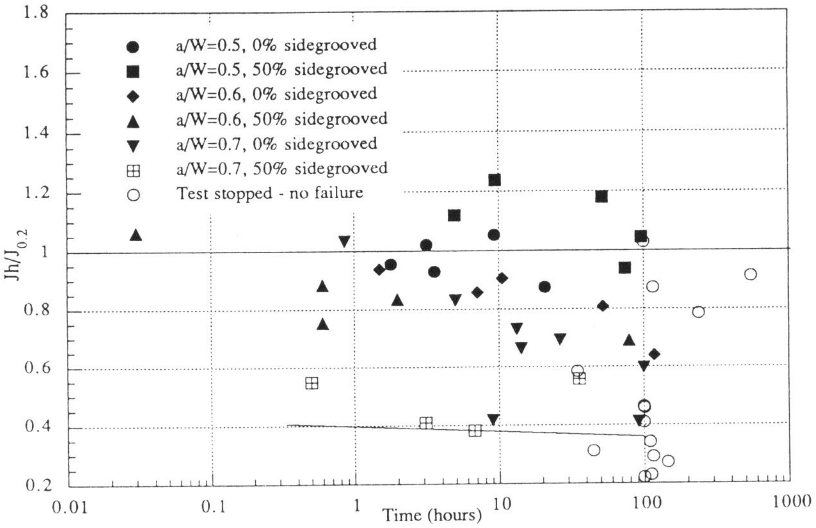

Figure 3. Load-hold test data showing J at hold (normalised by $J_{0.2}$) as a function of time to failure

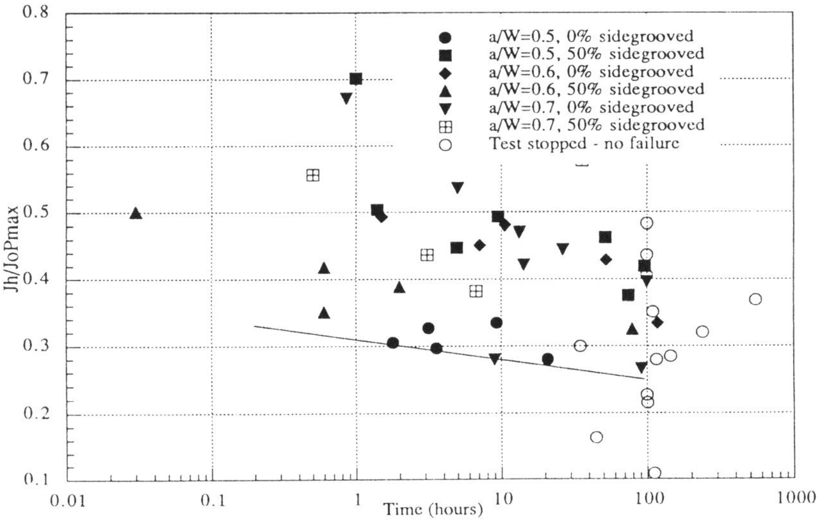

Figure 4. Load-hold test data showing J at hold (normalised by $J_{oPmax}$) as a function of time to failure