Effect of prior cyclic damage removal on high temperature low cycle fatigue endurance

S. R. Holdsworth\textsuperscript{a,*}, A. K. F. Maschek\textsuperscript{a,b}, L. Binda\textsuperscript{a}, E. Mazza\textsuperscript{a,b}

\textsuperscript{a}EMPA: Swiss Federal Laboratories for Materials Testing & Research, Überlandstrasse 129, 8600 Dübendorf, Switzerland
\textsuperscript{b}ETH Zürich, Institute of Mechanical Systems, Tannenstrasse 3, 8092 Zürich, Switzerland

Received 28 February 2010; revised 9 March 2010; accepted 15 March 2010

Abstract

In terms of fatigue life recovery, the beneficial effect of removing a surface layer from critical locations of components subject to high frequency elastic loading is well documented. Not so well known are the consequences of surface layer removal from parts previously subject to elasto-plastic low cycle fatigue (LCF) loading. The paper describes the results of a research project conducted to evaluate the effects of surface layer removal on subsequent LCF properties using uniaxial testpieces which have been prior cyclic deformed to different life fractions. Strain-controlled LCF tests performed on a 1\%CrMoV steel at 565°C with different strain amplitudes indicate that, following: \(i\) prior cyclic deformation (PCD) to nominal LCF life fractions of 0.5 and 0.8, \(ii\) subsequent surface damage layer removal, and \(iii\) test resumption; the consequent overall LCF endurances are at least as long as those accumulated without intermediate surface damage removal, and in some cases are significantly extended. Unlike the possibilities associated with elastic fatigue loading, LCF lifetimes are not fully recoverable following the removal of prior cyclic surface damage.

Keywords: Cyclic damage removal, LCF properties, cyclic softening, 1\%CrMoV

1. Introduction

The beneficial effect of removing surface layers from critical locations of components subject to high frequency elastic loading is well documented (e.g. [1,2]). The main consequence of such loading is the nucleation of micro-cracks at free (usually external) surfaces, and their ultimate development into large macro-cracks when the applied stress amplitude exceeds the limiting fatigue strength of the material. In such circumstances, the formation of cracks of a size larger than ~1-2 grain diameters occupies a significant fraction of life with little influence on the bulk properties of the material. By removing all evidence of such cracking through careful surface machining, component lives may be fully restored.

The consequences of surface layer removal from parts previously subjected to elastic-plastic low cycle fatigue (LCF) loading are not so well known. Cyclic plastic loading is not only responsible for fewer numbers of cycles to crack formation and development, but also for micro-structural changes resulting in cyclic softening and/or

* Corresponding author. Tel.: +41-44-823-4732; fax: +41-44-823-4252.
E-mail address: stuart.holdsworth@empa.ch.

1877-7058 © 2010 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2010.03.042
hardening (e.g. [3]). For example, low alloy ferritic steels typically cyclic soften due to dynamic recovery (e.g. [3,4]), whereas austenitic stainless steels may (depending on temperature) harden, or harden and soften, due to the development of planar, wall and vein dislocation structures, cross slip and sub grain formation (e.g. [3,5]).

The following paper is concerned with the behavior of 1%CrMoV steel which is known to cyclic soften during strain-controlled LCF tests to an extent depending on the temperature and strain amplitude (e.g. [6]).

**Nomenclature**

| Symbol | Definition |
|--------|------------|
| END | Endurance (step), second step of PCD-END LCF test |
| LCF | Low cycle fatigue (cyclic elasto-plastic high strain fatigue loading) |
| PCD | Prior cyclic deformation; also used to refer to first step of PCD-END LCF test |
| \( N, N_{2\%} \) | Number of cycles, number of cycles to 2% load drop (the adopted crack initiation endurance criterion) |
| \( N_{2\%} \) | Conventional LCF test crack initiation endurance |
| \( N_{PCD} \) | Number of cycles during PCD step of testing in two-step PCD-END LCF tests |
| \( N_{END,2\%} \) | Number of cycles to 2% load drop during END step of testing during two-step PCD-END tests |
| \( N_{Total,2\%} \) | Overall PCD+END test crack initiation endurance, i.e. \( N_{Total,2\%} = N_{PCD} + N_{END,2\%} \) |
| \( x \) | \( N_{PCD}/N_{2\%} \) fraction |
| \( y \) | \( N_{END,2\%}/N_{2\%} \) fraction |
| \( z \) | \( N_{Total,2\%}/N_{2\%} \) fraction |
| \( \varepsilon, \varepsilon_{\max} \) | Strain, strain amplitude |
| \( \sigma, \sigma_{\max} \) | Stress, maximum (tensile peak) stress |
| \( d\sigma_{\max}/dN \) | Change in maximum stress per cycle (softening rate in this paper) |

**2. Testing Details**

**2.1. Material**

Tests were performed on material taken from close to the surface of a 1%CrMoV turbine rotor production forging. The chemical composition and room temperature tensile properties of the steel are summarized in Table 1. The forging had been oil quenched from 950/970°C and tempered at 695/700°C. The test material exhibited a mid-to-upper bainitic microstructure typical of large production forgings manufactured in this class of creep resistant low alloy ferritic steel.

| C (wt.%) | Cr (wt.%) | Mo (wt.%) | Ni (wt.%) | V (wt.%) | \( R_{0.2} \) (MPa) | \( R_m \) (MPa) |
|---------|----------|----------|----------|----------|-----------------|----------------|
| 0.25    | 0.88     | 0.76     | 0.69     | 0.33     | 660             | 800            |

**2.2. Low Cycle Fatigue Tests**

Conventional LCF tests were first performed at 565°C with a strain rate of 0.1%/s to establish the influence of strain amplitude on crack initiation endurance. LCF tests were conducted in accordance with [7], with crack initiation endurances based on a 2% load drop criterion (i.e. \( N_{2\%} \)). These tests were performed with the specimen
geometry shown in Fig. 1b. Strain control was by means of an axial side-entry extensometer with a gauge length of 15mm.

A two-step testing procedure was adopted to evaluate the influence of prior cyclic damage removal on LCF properties. The first involved a PCD (prior cyclic deformation) step involving tests at 565°C using the testpiece geometry shown in Fig. 1a (i.e. with a 10mm gauge section diameter). These tests were taken to either 0.5, 0.2%, or 0.8, 0.2% cycles. Following the PCD step, 1mm was removed from the surface of the parallel gauge section of the specimen, around the whole diameter (i.e. Fig. 1b), and the test was continued at the same strain amplitude, at 565°C, to crack initiation, i.e. the END (endurance) step.

![Fig. 1. Specimen geometry details for: (a) PCD stage testing; (b) conventional and END stage LCF testing](image)

The 2% load drop criterion for crack initiation endurance in 10mm gauge section diameter testpieces typically equates to the presence of discretely distributed ~0.5-1.0mm deep thumbnail surface fatigue cracks. However, it is also known that isolated ≤0.5mm deep cracks may be present in LCF specimens of this type of steel at 0.5, 0.2% (e.g. [8]). With this experience, it was judged that any fatigue cracking damage generated during the PCD step would be removed when the gauge section diameter was reduced from 10 to 8 mm. Following diameter reduction, all specimens were penetrant dye checked and optically examined to confirm the absence of detectable residual surface cracking before proceeding to END step testing. In these circumstances, final test endurances were likely only to be influenced by the effects of prior cyclic deformation on material condition.

The results of conventional and two-step PCD-END LCF tests are summarized in Table 2.

### Table 2. Summary of Conventional and Two-Step PCD-END LCF Endurances

| LCF   | PCD (%) | END   | PCD + END |
|-------|---------|-------|-----------|
| ε₀ (%) | N₂₀ (%) | x     | y         | z         |
| ±0.70  | 503     | 255   | 0.5       | 249       | 0.5       | 504       | 1.0       |
| ±0.50  | 638     | 323   | 0.5       | 457       | 0.7       | 780       | 1.2       |
| ±0.25  | 6,423   | 3,283 | 0.5       | 3751      | 0.6       | 7,034     | 1.1       |
| ±0.70  | 503     | 408   | 0.8       | 123       | 0.3       | 531       | 1.1       |
| ±0.50  | 638     | 516   | 0.8       | 331       | 0.5       | 847       | 1.3       |
| ±0.25  | 6,423   | 5,253 | 0.8       | 5,247     | 0.8       | 10,480    | 1.6       |

Notes: N₂₀ is average of 3 conventional LCF endurances; x = N_PCD/N₂₀; y = N_END,2%/N₂₀; z = N_total,2%/N₂₀

3. Observations

### 3.1. Conventional LCF Properties

During strain-controlled LCF tests on uniaxial specimens of 1%CrMoV steel at 565°C, the tensile peak stress reduces with cycle number in the way shown for different strain amplitudes in Fig. 2. Typically, there is a rapid rate of softening during the first ~20% of life (Stage I, Fig. 2a), followed by a significant period of uniform softening at a relatively low steady-rate (Stage II), ultimately followed by apparently high rate Stage III softening. In low alloy ferritic steels, Stage III softening is mainly the consequence of macro-crack formation during which the rate of stress reduction reflects the rate of crack development in the specimen gauge length.
The LCF crack initiation endurance results determined in conventional tests for the investigated 1%CrMoV steel are contained in Fig. 3. There are three $N_{2\%}$ results for each of the three control strain amplitude, exhibiting good repeatability with a $\pm 7\%$ scatter at $\pm 0.7\%$ strain increasing to $\pm 20\%$ at $\pm 0.25\%$.

![Fig. 2. Three stage cyclic softening stress response in conventional strain-controlled LCF tests, and the dependence on strain amplitude](image.png)

![Fig. 3. The effect of cyclic surface damage removal on total LCF endurance, following 0.5.N2% and 0.8.N2% PCD cycles, in terms of; (a) total strain range, and (b) mid-life cycle plastic strain](image.png)

### 3.2. PCD-END LCF Tests

The results of the two-step PCD-END tests are summarised in terms of their total LCF crack initiation endurances in Fig. 3 (where total endurance is $N_{PCD} + N_{END,2\%}$). Removal of a 1mm deep surface layer has a small positive influence on total endurance when $x$ (the $N_{PCD}/N_{2\%}$ fraction) is 0.5. The positive effect of surface damage removal on total endurance is also relatively small, at high strain amplitudes, when $x$ is 0.8. However, life extension is more significant for the higher $N_{PCD}/N_{2\%}$ fraction when the strain amplitude is low (i.e. $z = 1.6$, Table 2).

The variations of tensile peak stress with cycle number for three strain amplitudes at $x$-ratios of 0.5 and 0.8 are respectively shown in Fig. 4 and Fig. 5. For an $x$-fraction of 0.5, there is little evidence of Stage I softening following re-machining for strain amplitudes of $\pm 0.50$ and $\pm 0.70\%$ (Fig. 4a), but a small indication at $\pm 0.25\%$ (Fig. 4b).
When prior surface cyclic damage is removed for a $N_{PCD}/N_{2\%}$ fraction of 0.8, there is more significant evidence of Stage I softening at all strain amplitudes, after re-machining, but most markedly at $\pm 0.25\%$ (Fig. 5b).

A comparison of Stage II softening rates before and after prior surface cyclic damage removal is summarized in Table 3. There is a systematic effect of strain amplitude on the Stage II softening rate, with $-d\sigma_{max}/dt$ reducing in magnitude with reducing strain amplitude. Moreover, Stage II softening rates are consistently lower after cyclic surface damage removal.

Table 3. Summary of Stage II Softening Rates Before and After Surface Cyclic Damage Removal

| $\epsilon_0$ (%) | $N_{PCD}/N_{2\%}$ (%) | $d\sigma_{max}/dt$ (MPa/cycle) | $d\sigma_{max}/dt$ (MPa/cycle) |
|------------------|------------------------|-------------------------------|-------------------------------|
| $\pm 0.70$       | 0.5                    | -0.094                        | -0.053                        |
| $\pm 0.50$       | 0.5                    | -0.062                        | -0.036                        |
| $\pm 0.25$       | 0.5                    | -0.005                        | -0.003                        |
| $\pm 0.70$       | 0.8                    | -0.094                        | -0.048                        |
| $\pm 0.50$       | 0.8                    | -0.055                        | -0.041                        |
| $\pm 0.25$       | 0.8                    | -0.005                        | -0.002                        |

Fig. 4. The influence of strain amplitude on cyclic stress response in strain-controlled PCD-END LCF tests before and after cyclic surface damage removal following $0.5\% N_{2\%}$ cycles.

Fig. 5. The influence of strain amplitude on cyclic stress response in strain-controlled PCD-END LCF tests before and after cyclic surface damage removal following $0.8\% N_{2\%}$ cycles.
3.3. Crack Development

LCF cracking in 1%CrMoV steel at 565°C initially develops as a continuous distribution of micro-cracks to a depth of ~1-2 grain diameters at a relatively early stage of life. With sustained cyclic plastic loading, a small number of dominant cracks develop to become macro-cracks (e.g. Fig. 6). Isolated thumbnail cracks with a depth of ≤0.5mm may be present at ~0.5 $N_{2\%}$ cycles [8]. Typically, macro-cracking in conventional sized LCF testpieces is more extensive after $N_{2\%}$ cycles, being discretely present as ~0.5-1.0mm deep thumbnails.

Fig. 6. Crack development along gauge length of 1%CrMoV testpiece subjected to strain-controlled LCF loading at 565°C (for >$N_{2\%}$ cycles)

4. Discussion

4.1. Fatigue Life Extension

A main finding of the study is that the removal of a 1mm surface layer from the gauge diameters of LCF specimens after 0.5 $N_{2\%}$ or 0.8 $N_{2\%}$ cycles can extend the overall fatigue lifetime of such testpieces, in particular for low strain amplitude loading. Importantly, LCF lifetime is not fully recovered by surface damage removal. This is in contrast to well established experience for cases in which prior loading is cyclic elastic. In such circumstances, the evidence indicates that fatigue lifetimes can be fully recovered after surface damage removal (e.g. [1,2]).

Fatigue loading involving cyclic plastic deformation is responsible not only for the formation of surface cracks, but also for significant changes to the micro-structural condition (as reflected by the peak tensile stress response, e.g. Fig. 2a). In 1%CrMoV steel, this involves the transition from an initially highly tangled dislocation structure in the as-received quality heat treated condition to a relatively well ordered sub-grain structure at the end of fatigue life. During this process of dynamic recovery, the initially tangled dislocation structure is first transformed into ill-defined sub-cells and then into a well-defined sub-grain structure [3]. The transition from cells to sub-grains is through the rearrangement of tangled dislocations (by climb, cross-slip and glide [9]) into low angle boundaries as well as the annihilation of dislocations in cell interiors. These changes to the microstructure are not limited to a near surface layer, but occur throughout the entire gauge sections of uniaxially loaded testpieces. Consequently, removal of a surface layer following cyclic plastic LCF loading does not eliminate all trace of the prior deformation history, only the surface damage associated with crack formation.

At higher strain amplitudes, the cycles to crack initiation following re-machining (i.e. $N_{END,2\%}$ in Table 2) appear to be similar, irrespective of $N_{PCD}/N_{2\%}$ fraction. At the lowest strain amplitude of ±0.25%, $N_{END,2\%}$ is significantly greater for $x = 0.8$ than for $x = 0.5$, suggesting that the resistance to LCF crack formation and development improves with the extent of cyclic softening.
4.2. Cyclic Softening

Cyclic softening in 1%CrMoV steel subjected to strain-controlled LCF loading occurs in three stages. Following a rapid rate of softening during the first ~20% of life (Stage I, Fig. 2a), there is a significant period of uniform softening at a relatively low steady-rate (Stage II), ultimately followed by apparently high rate Stage III softening. In low alloy ferritic steels, Stage III softening is mainly the consequence of macro-crack formation during which the rate of stress reduction reflects the rate of crack development in the specimen gauge length.

There is not yet a complete understanding of the reasons for the different softening rates during Stages I and II, although work is underway which should clarify the situation [3]. It is conceivable, that a main part of the transition from the initially highly tangled dislocation structure to a relatively well ordered sub-grain structure occurs during Stage I. The relatively low steady-rate Stage II softening could then be simply due to the combined effects of sub-grain growth and micro-crack development.

The evidence in Table 3 indicates that Stage II softening continues after surface metal removal, but at a significantly lower rate. This is consistent with the assumption that softening in this regime is due both to micro-structural change and to fatigue crack development, with the latter being at a much lower rate in prior softened material.

5. Conclusions

The paper describes the results of a research project conducted to evaluate the effects of surface layer removal on subsequent LCF properties using uniaxial testpieces which have been prior cyclic deformed to different life fractions. Strain-controlled LCF tests performed on a 1%CrMoV steel at 565°C with different strain amplitudes indicate that, following: i) prior cyclic deformation (PCD) to nominal LCF life fractions of 0.5 and 0.8, ii) subsequent surface damage layer removal, and iii) test resumption; the consequent overall crack initiation endurances are at least as long as those accumulated without PCD, and in some cases are significantly extended.

LCF lifetimes are not fully recovered by cyclic surface damage removal following periods of prior cyclic deformation.

There is evidence (to be confirmed by micro-structural evaluation) that low steady-rate Stage II cyclic softening is due both to the growth of sub-grains established during Stage-I softening and to surface fatigue microcrack development.

Following intermediate surface damage removal, the rate of Stage II softening is reduced. The reduced steady-rate softening kinetics are likely to be due to an increase in the resistance to LCF crack development in the prior cyclic softened steel.

Acknowledgement

Helpful discussions with Mr T Mayer (EMPA) are duly acknowledged.

References

[1] Frost NE, Marsh KJ, Pook LP. Metal Fatigue. Oxford: Clarendon Press; 1974.
[2] Sharp PK, Liu Q, Barter, SA Baburamani, P Clarke G. Fatigue life recovery in aluminium aircraft structure. Fatigue and Fracture of Engineering Materials and Structures 2002;25(2):99-110.
[3] Mayer T, Pham MS, Solenthaler C, Janssens KGF, Holdsworth SR. The effect of sub-grain formation and development on cyclic response in engineering steels, Proc. 18th European Conf. on Fracture ECF18, DVM, Dresden, 30.8-03.9.2010.
[4] Plumbridge WJ, Bartlett RA, Cyclic response of a 1Cr-Mo-V steel with bainite and ferrite microstructure. Int. J. Fatigue 1982;4(4):209-216.
[5] Gerland M, Alain R, Ait Saadi B, Mendez J. Low cycle fatigue behaviour in vacuum of a 316L-Type austenitic stainless steel between 20 and 600°C – Part II: Dislocation structure evolution and correlation with cyclic behaviour. Materials Science & Engineering 1997;A229:68-86.
[6] NRIM. Data Sheets on the elevated temperature properties of 1Cr-1Mo-0.25V steels forgings for turbine rotors and shafts (ASTM A470-8). NRIM Creep Data Sheet No. 9A; 1979.

[7] ISO 12106. Metallic materials – Fatigue testing – Axial-strain-controlled method. International Standards Organisation; 2003.

[8] Denk J. Quantification of the load drop crack initiation criterion of LCF tests of ferritic steels. In: Portela PD, Beck T, Okazaki M, editors. Proc. 6th Intern. Conf. on Low Cycle Fatigue, LCF6, Berlin, 8-12 Sept; 2008, p. 247-254.

[9] Tegart WJMcG. Dynamic recrystallisation – An historic perspective. Material Science Forum 1993;113-115.