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Spectrum load fatigue—underlying mechanisms and their significance in testing and analysis

R. Sunder

BiSS Research, 41A, 1A Cross, AECS 2nd Stage, Bangalore 560 094, India

Abstract

The constant amplitude fatigue process is driven by cyclic slip and surface chemistry. These in turn are affected by crack geometry, crack closure and crack-tip stress state, including residual stress. The sensitivity of these factors to spectrum loading determines durability and residual life under service load conditions. Cyclic slip forms the basis for the Rainflow cycle-counting technique and is therefore an integral part of any spectrum load fatigue analysis or test. Assessment of the relative significance of operative mechanisms impacts quality and cost effectiveness of spectrum load tests and also, the reliability of life predictions.

Keywords: Cyclic slip; Crack geometry; Crack-tip stress state; Crack front incompatibility; Rainflow; Residual stress; Spectrum load fatigue

1. Introduction

Understanding of spectrum load fatigue has advanced significantly over the past 50 years, aided by computer-controlled servo-hydraulic test technology, numerical modeling and electron microscopy. The continuous requirement of balancing performance with durability calls for rigorous testing and analysis to ensure safe and economical operation of machines and structures. From initial applications in the transportation and power sectors, fatigue design today extends to virtually every engineered product, spurred by global competition, customer awareness and liability clauses.

The significance of service load environment in controlling cumulative damage is universally recognized. As early as 1939, Gassner had developed a standardized block program load sequence [1]. Early fatigue models connected history-sensitive residual stress to non-linearity in cumulative fatigue damage [2–4]. Discovery of the phenomenon of fatigue crack closure in tension provided the basis for a variety of analytical models to predict fatigue crack growth under spectrum loading [5–7].

State-of-the art modeling of spectrum load fatigue integrates a variety of inputs. These include finite element modeling, constitutive modeling to simulate material cyclic inelastic and time-dependent response and crack closure behavior under cycle-by-cycle application of pseudo-random service loading. Though such simulation may be complex, it still appears incomplete. A single mechanism such as closure cannot bridge deviations from constant amplitude test conditions. Fatigue is driven by the synergistic action of multiple mechanisms, all of which are sensitive to load history [8].

This study covers individual fatigue mechanisms and their quantitative significance to spectrum load fatigue. These include crack closure, residual stress and crack front geometry. The basis for Rainflow analysis and its application to spectrum load fatigue is discussed. The paper is an attempt to underscore the significance of individual mechanisms involved in spectrum load testing and modeling.

2. Similarity approach in fatigue

2.1. Crack formation life

Notch fatigue analysis is based on translating applied (usually elastic) load excursions to local (notch–root) inelastic stress–strain response [9–11]. The similarity approach in estimating life to crack formation hinges on the premise that similar local cyclic stress/strain amplitude and similar local mean stress will cause similar life

E-mail address: r.sunder@vsnl.com (R. Sunder).

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to crack formation, independent of notch geometry and load history.

With respect to the state-of-the-art in modeling fatigue life to crack formation under spectrum loading, the following aspects are noteworthy:

1. Notch root stress and strain *amplitude* are history-independent, provided material response is cyclically stable. History sensitivity is assumed to be driven *exclusively* by the local mean stress component [2].
2. As shown in Fig. 1, history sensitivity of local mean stress is determined by notch root inelasticity. In the absence of monotonic inelasticity, stress-history effects will not be apparent. Further, in the absence of cyclic inelasticity, local mean stress for a given applied nominal load cycle will not be subject to a history-dependent envelope of variation. In the event of local *cyclic inelastic* response, sequence-sensitive variation in cumulative fatigue damage can be defined as an envelope bounded by finite extremes that can be defined from load spectrum statistics *without recourse* to cycle-by-cycle analysis [12].
3. The similarity approach which forms the basis for local stress–strain analysis is not sensitive to notch stress gradient, surface finish and other surface processing including heat treatment, shot peening and coatings.
4. Initiation life is to a specified crack size. It would follow that life to crack formation by definition includes some extent of crack growth. While proportions are a subject of debate, it appears reasonable to expect that notch root stress-amplitude and mean stress will determine crack formation and short crack kinetics [13].
5. While the effect of the amplitude content may be directly related to the extent of cyclic slip reversal, the mean stress effect on fatigue is only known by *correlation*—without identification of any underlying mechanism. Recent research suggests that the mean stress effect in fatigue may be environment-related.

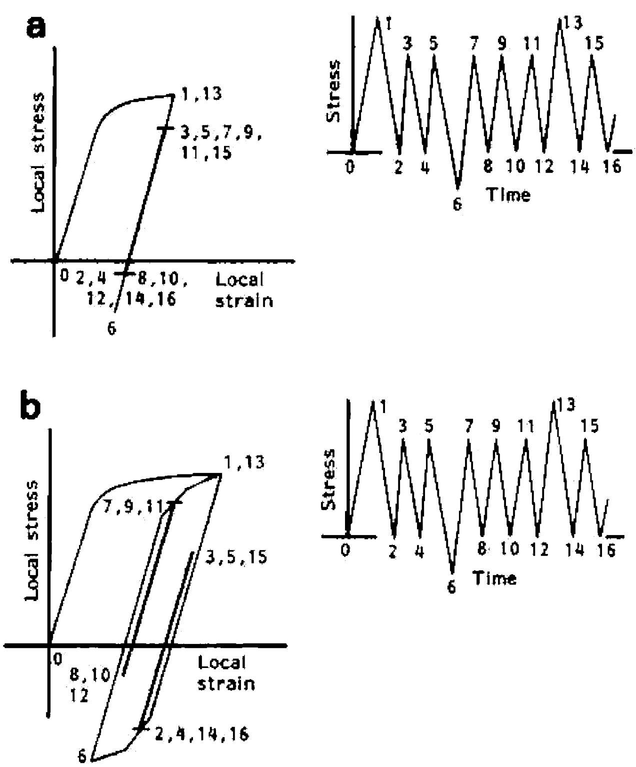

Fig. 1. Simulated notch root response to a simple variable amplitude load sequence. Monotonic yield in tension causes compressive residual stresses. If the excursion 1–6 does not cause *reverse* yield, all intermediate cycles of similar nominal mean and amplitude will see *history-independent* local mean stress (as in 2–5, 7–12, 14–16 of (a)). However, in the event of notch root *cyclic inelasticity* as in (b), the same cycles can see different local mean stress (7–12 versus 2–5, 14–16).

2.2. Fatigue crack growth

Applied stress intensity range and stress ratio are accepted in engineering practice as primary similarity criteria for fatigue crack growth [14,15]. These are accompanied by 'coincidental' criteria including monotonic and cyclic-plastic zone size, crack-tip radius, crack front geometry and crack plane. While monotonic and cyclic plastic zone size and crack-tip radius are directly related to applied ΔK and R, the other parameters steadily evolve in constant amplitude fatigue, irrespective of applied stress level and crack geometry. As a consequence, crack growth rate, da/dN readily correlates with ΔK and R across a wide variation in specimen geometry and applied stress level. In fact, this forms the basis for the application of fracture mechanics to crack growth analysis. Standard practices such as ASTM E-647 have evolved for the generation of growth rate data on standard laboratory coupons. It is assumed that the same data can be extrapolated to crack geometries and load levels of engineering interest, including component level application.

Load interaction effects may render an impression of complexity to spectrum load fatigue crack growth. Let us consider this as one of the deviations in similarity criteria. The discussion is focused on three major independent factors: crack front geometry, crack closure and residual stress.

2.3. Crack front geometry

The 'coincidental' criteria listed above may create the impression of being uniquely related to ΔK and R. It will not be the case under spectrum loading and need not be the case even under constant amplitude loading. This is illustrated by a comparison of the three fractures shown in Fig. 2 and obtained from tests in vacuum, air and salt water respectively [16]. These fatigue fractures were obtained under constant amplitude loading at 98 MPa on

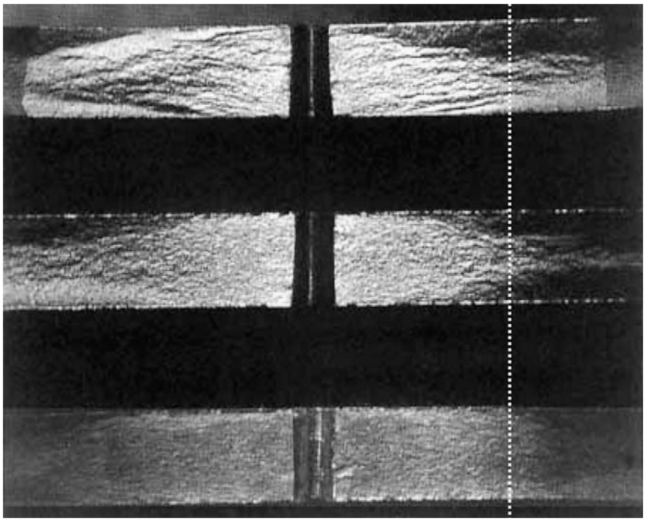

Fig. 2. Fatigue fractures from identical center-cracked 6 mm thick 7075-T6 specimens, all tested at $S_{max} = 98$ MPa and $R = 0.1$ [16]. Top: vacuum; middle: air; bottom: salt water. Crack growth is known to be accelerated in air and even more so in salt water by comparison to vacuum. The dotted line clearly indicates that contrary to expectation, shear lip development is highly retarded in salt water by comparison to vacuum. These pictures provide compelling evidence that crack geometry is environment-sensitive and cannot be assumed to be a similarity parameter that is solely dependent on stress state, ΔK or crack growth rate.

identical specimens cut from 7075-T6 Al–Cu–Zn alloy. The fatigue crack front rotates from normal to shear plane with increase in crack growth rate [16]. Had the three fractures shown in Fig. 2 been obtained under identical test environment, one would have readily concluded that they are arranged top-down in *decreasing* order of stress level. However, fatigue crack growth rate in air is accelerated by comparison to vacuum and is even greater in salt water. Thus, the three fractures are in fact arranged top-down in *increasing* order of growth rate! Important conclusions emerge from these experiments:

1. Crack extension mode is sensitive to the combined action of crack-tip stress state, the extent of reverse loading as well as environment [17]. Crack front geometry may therefore be treated as an *independent* similarity criterion.
2. Load history is a potential source of deviation in similarity criteria through distortion of crack front geometry [8].
3. Even under constant amplitude loading, a switch in environment can cause a history-sensitive interaction effect associated with incompatibility in crack front geometry.

In an attempt to quantify the effect of crack front incompatibility, Schijve [18] performed fatigue crack growth tests on edge-notched coupons with spark-eroded crack initiators of different geometry and orientation. These experiments induced retardation in growth rate of up to a factor of two, which was accounted for by measured differences in specimen compliance. Thus, applied stress intensity range multiplied by instantaneous compliance relative to a normal crack plane served as an adequate similarity criterion for crack growth rate.

The above experiment involved macroscopic dimensions and provided a mechanics-based solution to resolve dissimilarity. The solution implies that ΔK must be corrected for crack front geometry sensitive decrease in compliance. It would follow that growth rate data plotted against such a suitably corrected ΔK would represent ‘true’ resistance to fatigue crack growth. Growth rate given by such a curve represents a certain maximum. Any deviation in crack front from the plane normal to loading axis would lead to a *reduction* in growth rate associated with decreased compliance[1].

The mechanics approach may be extended to load history-induced crack front incompatibility at the microscopic scale. Typical examples appear in Fig. 3. Fig. 3a shows the consequences of hold-time at elevated temperature in vacuum that leads to crack-tip blunting [19]. Resumption of fatigue cycling will necessarily involve re-initiation because prevailing growth rate is associated with a crack-tip radius much smaller than the prevailing (blunt) tip. As shown in the figure, this results in the initiation of two independent fatigue cracks, one of which will subsequently arrest. Even the blunt crack tip has a radius of only a few microns implying almost instantaneous crack re-initiation. Dwell time at elevated temperature in air forces a transition of crack growth from transgranular to intergranular (see Fig. 3b) [20], with simultaneous tunneling. In this case, initial retardation of sustained load cracking is associated with the transgranular crack front. There is also retardation on return to fatigue cycling because the crack front is now convoluted and also perhaps multiple intergranular cracks formed (Fig. 3c). The presence of cracks on parallel planes and their possible inclination from the normal (kinking) will reduce crack driving force. Fig. 3d shows crack branching caused by change in loading amplitude. Crack branching was apparently caused by instantaneous change in growth mechanism (Mode I/II) that enforced a change in crack plane as well as branching.

The experiments from which Fig. 3a–d were obtained were specifically designed to ensure the absence of plasticity or closure-related load interaction effects. One may conclude that crack front geometry- related load interaction effects may be handled from a strictly mechanics angle, assuming of course that no associated change in

[1] The exception would be high stress intensity levels, where a flat crack with a straight front may be more prone to quasi static crack extension by virtue of applicability of K_{1c} as opposed to K_c.

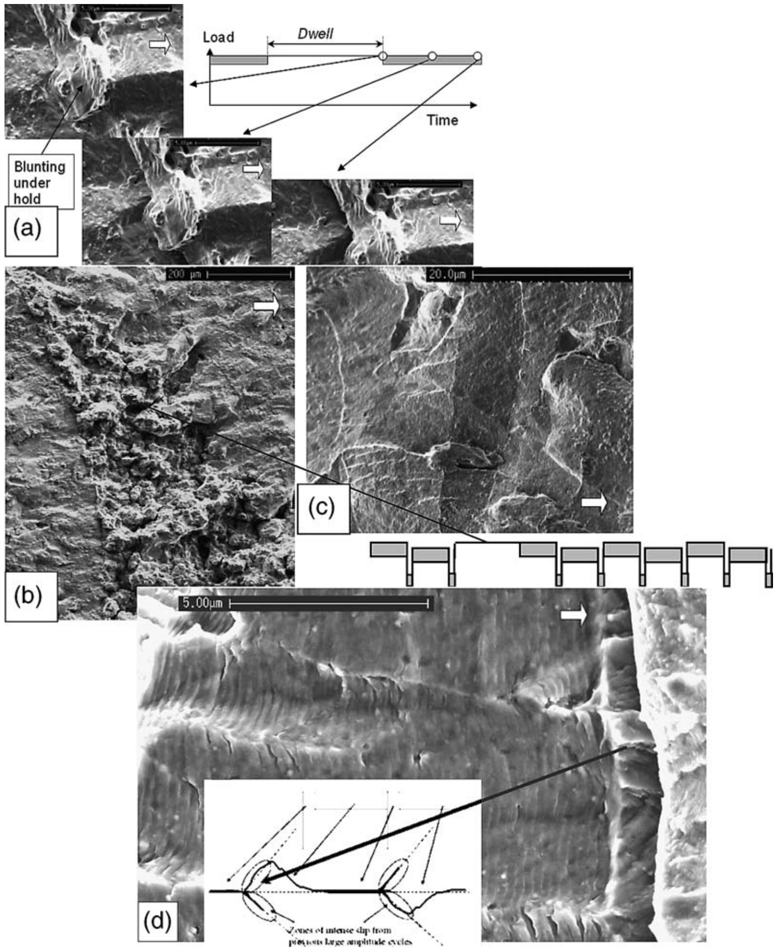

Fig. 3. (a) Crack tip blunting during elevated temperature hold-time in vacuum. Resumption of fatigue cycling causes two cracks to initiate out of the blunted front IN-100 at 650 °C in vacuum [19]. (b) Hold-time at elevated temperature in air causes sustained load inter-granular cracking and associated retardation due to crack front incompatibility both at the commencement of hold time (b) as well as after return to fatigue cycling (c). IN-100 at 650 °C in air [19]. (d) Crack branching caused by switch in load cycle amplitude [20]. In these experiments, crack closure effects were marginalized by keeping stress ratio high and S_{max} = Const. Al-alloy in air.

mechanism occurs. The modeling process would essentially result in computation of a reduced ΔK as a consequence of CFI. Such a reduction would be analogous to corrections for compliance [18], crack bridging or shielding [21] and at a macroscopic scale, to a crack growing under an un-cracked stiffener, or, at a hole [22] under a pre-torqued fastener [23].

2.4. Fatigue crack closure

The discovery of crack closure some thirty years ago [24] made it possible to make spectrum load fatigue crack growth predictions based on modeling crack opening stress variation as a function of load history [6]. Earlier efforts at modeling [3,4] were largely an approximating exercise with transient retardation functions requiring empirically determined constants. The presence of closure essentially redefines similarity criteria by replacing the combination of ΔK and R by $\Delta K_{eff,}$ the range of stress intensity over which, the crack is fully open.

Fatigue crack closure has been widely researched over the past three decades and is by far the most 'popular' variable for data correlation and crack growth prediction models. Yet, its measurement and sometimes even its relevance are a subject of controversy [25,26]. Fig. 4a,b provides compelling evidence indicating the presence of closure under tensile loading. Equally-spaced striations in Fig. 4a [27] obtained under repeated application of the specially designed load sequence with constant S_{max} cannot be explained by any mechanism other than crack closure. If there was no closure, no two striations would be alike, given the power relationship between crack growth rate and applied load range. Fewer equal striations in the mid-thickness region indicate reduced crack closure, which is to be expected given local constraint. Fig. 4b provides equally compelling evidence of the presence of crack closure [28]. The figure shows hyster-

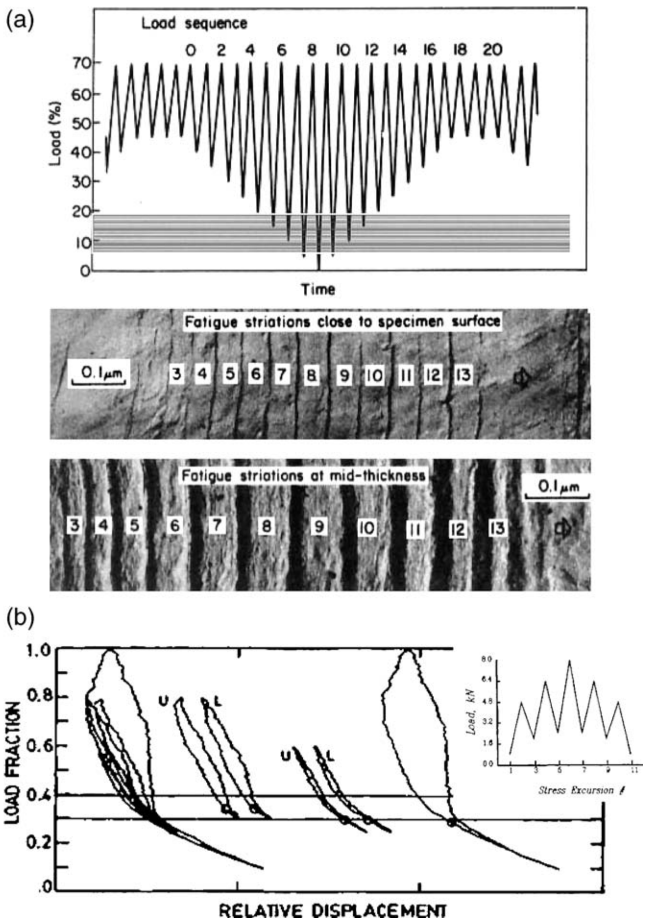

Fig. 4. (a) Compelling fractographic evidence of crack closure in an Al-alloy [27]. No other mechanism can explain equally-spaced striations under a variable amplitude sequence. Note greater level of closure at the specimen surface by comparison to the mid-thickness region (b) Laser interferometry-based near-tip measurements clearly indicate greater hysteresis (reverse slip) at higher stress ratio [28] as shown by comparison of embedded cycles of equal magnitude. Only closure can explain this. Test on Al-alloy C(T) specimen.

esis in force versus near-tip strain, measured by laser interferometry across points spaced about 0.1 mm apart and less than 0.1 mm ahead of the crack tip. If the crack was open throughout the load sequence, embedded load cycles of equal range would also see equal hysteresis, which is a measure of near-tip slip reversal. The embedded cycle of lower stress ratio sees negligible hysteresis, indicating greater extent of crack closure.

While evidence of fatigue crack closure may be compelling, the evidence on the magnitude of crack closure (and therefore its significance to spectrum loading) is not so self-evident. Irrespective of material and applied loading conditions, we have not been able to fractographically obtain closure levels in excess of 20–30%[2]. If one assumes mean closure levels under 25% across the specimen thickness, a 100% overload can cause a factor of three peak reduction in post-overload crack growth rate, assuming exponent $m = 3$ in the growth rate equation. Actual measurements of post-overload retardation often indicate retardation of an order of magnitude, if not more [30]. In fact, Petrak's study [30] on material heat-treated to different yield stress clearly points to a correlation between increasing retardation and decreasing yield stress. However, no such correlation appears to exist between yield stress and closure. Such empirical evidence indicates that models may require exaggerated estimates of closure to explain observed levels of retardation. Finally, while models would predict steady increase in proportion of closure with increasing K (onset of plane stress conditions), retardation effects actually diminish with increasing growth rate.

As pointed out by Schijve [8] and in a more recent review by Skorupa [31], a multitude of mechanisms combine to cause load interaction effects. Crack closure and several forms of crack front incompatibility are two major mechanisms. Both of these can be handled on a mechanistic basis, i.e., in a manner that corrects ΔK_{eff}. Residual stress is the third major load interaction mechanism and its operation does not even depend on the presence of a crack (as it is known to affect life to crack formation). Residual stress figures in load interaction models for both crack initiation as well as propagation [2–4]. However, the *operative mechanism* of the residual stress was addressed only recently. Its isolation is complicated by the possible combined action of crack closure, and in fact, it is even suggested that crack closure is, partly, a consequence of residual stresses [32].

2.5. Crack-tip stress state and the residual stress effect

Mechanism isolation facilitates quantification and avoids misinterpretation. In order to isolate the residual stress effect, a series of experiments were designed to show up load interaction effects in the *absence* of closure. The experiments were focused on near- and sub-threshold fatigue, which accounts for the bulk of fatigue life. A detailed description of these experiments can be found elsewhere [33,34]. In these tests, crack growth was caused by a large number of high-R, low-amplitude cycles, which are interspersed with a few large cycles of low-R. These large cycles serve as markers on the fracture surface indicating growth during the large number of near-threshold high-R cycles. They also keep the crack fully open during the small cycles by 'beating' closure down to less than 50% of the lowest $S_{\min}$ in the high-R steps. A typical fractograph from a notched 2014-T6511 alloy notched coupon appears in Fig. 5.

If crack closure was the sole operative load interaction

[2] The exception is notch root cracking, where compressive residual stress can push local stress ratio down, causing an apparent increase in crack closure level [29].

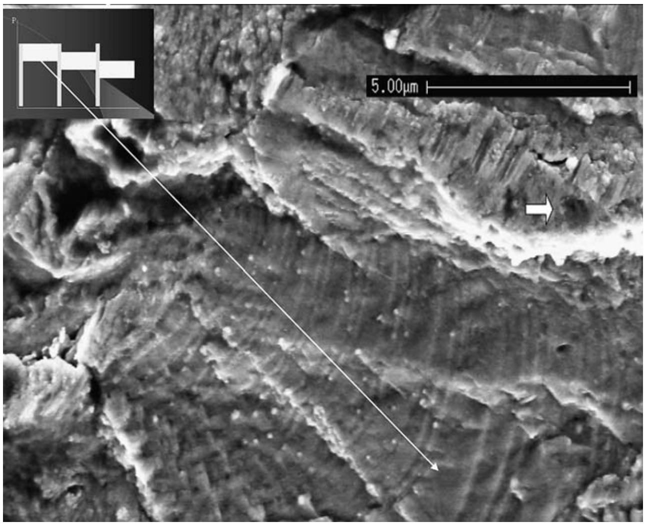

Fig. 5. Typical naturally initiated notch root short crack in Al-alloy 2014-T6511 under programmed loading shown at top left. The sequence consists of three steps of 2000 Hi-R cycles separated by ten Lo-R marker cycles. Each band seen between markers is from 2000 cycles. The Hi-R steps of equal magnitude were applied at $R = 0.73$, 0.69 and 0.64. Note the ~3× reduction in growth rate at $R = 0.64$ even though $S_{\min}$ in the step was twice the S_{op} for the block. Note also the remarkable consistency in marker spacing even though crack size was less than 0.1 mm, indicating the total absence of scatter associated with the so-called 'short-crack effect'. Similar results were obtained at near-threshold growth rates in numerous repeat tests under different stress levels [33]. The retardation effect was attributed to residual stress from the Higher-R steps. The effect vanishes in vacuum, suggesting that residual stress operates through environmental action.

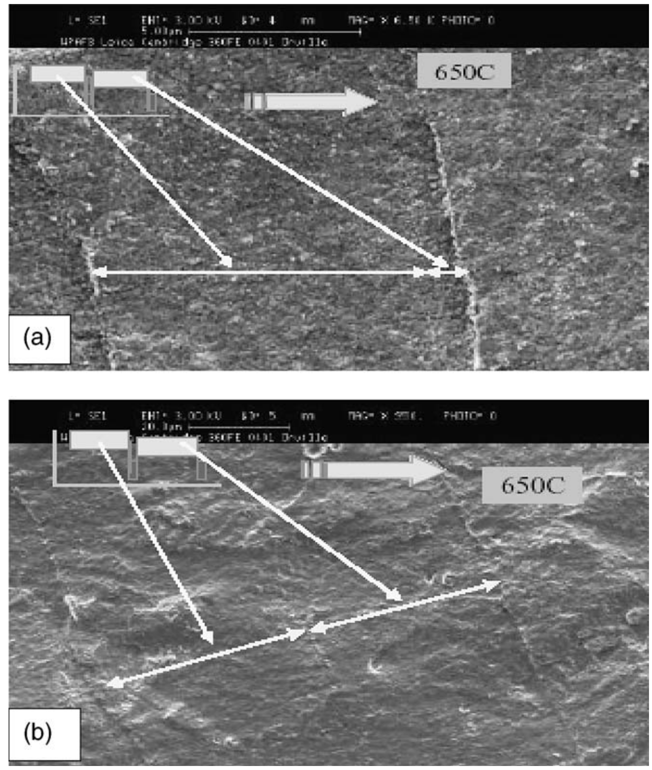

Fig. 6. (a) Retardation as high as 10:1 observed under near-threshold conditions on a 5 mm thick compact tension specimen cut from a nickel-base superalloy, tested in air at elevated temperature. The test program was reduced to two steps and marker loads changed to facilitate fractography. Each band of growth is from 2000 cycles of loading. The observed retardation rapidly diminishes to vanishing proportions with increasing growth rate. (b) The retardation effect is totally absent in vacuum, confirming the possibility that the operative fatigue mechanism of crack-tip residual stresses is moderation of environment ingress [34]. This conclusion is supported by the effect switching 'On' and 'Off' when environment is switched. If the effect was a closure-related, a transient region would be present.

mechanism, crack growth bands from the three high-R steps should be identically spaced, as in fact was the case for long cracks at intermediate range growth rates. However, as growth rate approaches near-threshold levels, it appears to become extremely sensitive to even minor prior overloads as is the case in three-step loading. As shown in Fig. 5, growth rate in the lowest of the high-R steps can be several times lower than at the highest of the high-R steps, even though the difference in R between the two extreme steps is less than 0.1.

The experiments were initially performed on Al-alloys [33]. Similar trends were observed in IN-100 nickel-base super-alloy tested at elevated temperature [34] (Fig. 6). Surprisingly, the effect totally vanished when the experiments were repeated in vacuum (see Fig. 6b). The marker bands in vacuum were equally spaced, indicating insensitivity to both stress ratio as well as stress history. When the environment was alternated in the Al-alloy test between air and vacuum, the retardation effect also simultaneously switched on and off, indicating the absence of any time-dependent phenomenon or a carry-over from the previous environment, such as oxide formation. For the same reason, crack closure is also ruled out. If the effect was closure related, at least a microscopic transient zone should have been seen on switching from air to vacuum and vice versa.

As noted earlier, closure was avoided in these experiments by focusing on high stress ratio and by applying periodic underloads. Also, as the experiments were all in the near-threshold regime, crack growth plane and crack front geometry did not vary, precluding any effect of crack front incompatibility. Thus, by a process of elimination, the effects were attributed to environmental action as moderated by residual stress. This should not come altogether as a surprise given the fractographic evidence in Fig. 2. Environment appears to control the very mechanism of fatigue crack extension. Based on this premise, a model was recently proposed [35] of crack extension by environment-induced brittle micro-fracture (BMF), whereby, crack-tip material exposed during the previous load cycle is embrittled by diffusing gaseous atoms during the rising load cycle and associated high hydrostatic tensile stress. As a consequence of such cyclic embrittlement, crack-tip material is unable to accommodate accumulating slip from the interior, leading to crack extension by cleavage in Mode I or II.

As diffusion (*physics*) and reaction (*chemistry*) are sensitive to local hydrostatic stress, residual stresses assume significance in environmental fatigue including fatigue in air. The significance of the BMF model for spectrum fatigue lies in moderation of environmental fatigue by residual stresses. Compressive residual stress will constrain the diffusion process, while tensile residual stress will promote it. Unlike closure which induces delayed retardation, the effect of residual stress is immediate, which explains why retardation after overloads does not have to be delayed. The model also explains load interaction effects in the crack formation stage where a wake (and therefore closure) is absent.

If moderation of environmental action is indeed an important operative mechanism of residual stress, it would follow that protective coatings and residual stress operate in the same manner. Acceptance of this model would also imply *irreconcilable* limitation of the similarity approach. The presence of residual stress essentially means a different operational environment at the crack tip, rendering laboratory da/dN versus ΔK data or even S–N curves unsuitable for extrapolation to spectrum fatigue. A possible simplification may be to treat the phenomenon as largely near-threshold by nature and assume its approximation by a shift in threshold stress intensity. A multi-mechanism synergistic model based on these considerations is discussed elsewhere [20].

Schijve provides a review of the significance of flight-simulation fatigue tests [36], while general guidelines on spectrum load testing have been recently summarized by Wanhill [37]. In summary, crack closure, residual stress and crack front incompatibility (including crack-tip shape, blunting, kinking, branching and front orientation) are significant load interaction mechanisms. We now proceed to discuss Rainflow cycle counting technique that is essential for spectrum load testing and analysis.

3. Rainflow cycle counting and applications

Cyclic slip reversal constitutes the underlying mechanism of the fatigue process. Fatigue damage cannot be computed for incomplete load cycles, where slip reversal would also be incomplete. This concept forms the basis for the Rainflow cycle counting procedure [38]. The validity of Rainflow and its wide acceptance in service load data acquisition, analysis and testing for durability may be attributed to its sound conceptual foundation.

The significance of the concept of slip reversal completion in analyzing load-time histories is seen from the hypothetical load sequence in Fig. 7a, representing a multitude of small load cycles embedded in a single major cycle. If these small cycles were ignored, the cycle would appear as shown in Fig. 7b. Each embedded cycle can induce notch root (or crack tip) slip reversal. All

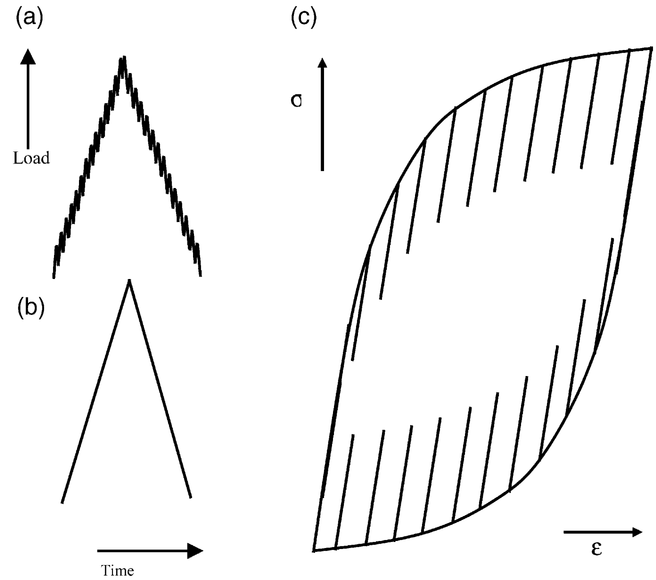

Fig. 7. Schematic illustration of the significance of Rainflow cycle counting. The load sequence (a) contains innumerable small load cycles embedded within a large cycle that appears separately as (b). The hysteretic stress–strain response in (c) demonstrates that the inclusion of the small embedded cycles does not overshadow the major cycle. The Rainflow cycle counting technique is based on the concept of closed stress–strain loops. Failure to identify closed cycles would result in neglecting the major loop seen in (c) due to the cycle shown in (b).

these tiny stress-strain loops are embedded within a major hysteresis loop shown in Fig. 7c. Representing an arbitrary load–time history in terms of a hypothetical stress–strain response permits graphic discrimination of individual *closed* cycles in the sequence. The Rainflow cycle counting procedure [38] uses this in an algorithm whose description can be found in ASTM E-1049. In the process of counting smaller embedded cycles, the Rainflow procedure does not overlook extreme peaks and valleys that may be spaced apart in time. Without this ability the significance of major events in a duty cycle, such as the Ground–Air–Ground cycle for a transport aircraft may be diluted by break-up into smaller intermediate excursions. This is highlighted by Fig. 8 that compares cycle counts from different procedures [39].

While Rainflow was initially developed for fatigue analysis under random loading for life to crack formation, its extension to fatigue crack growth is connected with the treatment of crack extension as a consequence of crack-tip slip reversal. In a strict sense, Rainflow for crack growth must be performed on K-history, rather than on stress history. A growing crack *theoretically* makes the two different. However, Rainflow would still be applicable, assuming that extreme stress-intensity events repeat before noticeable crack-extension, particularly at near-threshold and intermediate crack growth rates. Fig. 9 offers fractographic evidence in support of

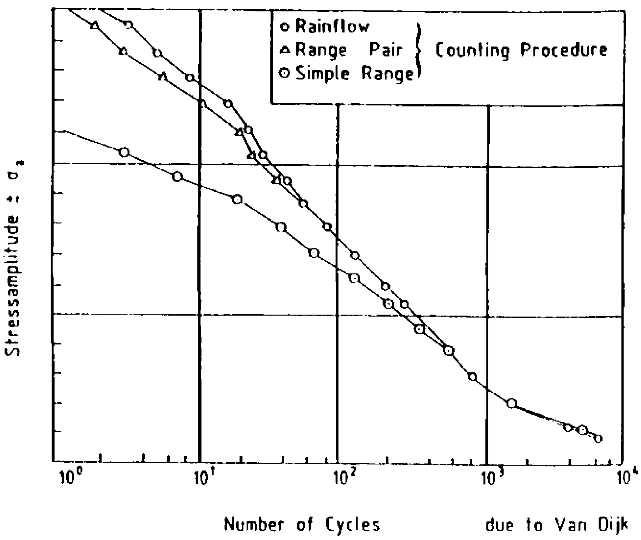

Fig. 8. Counted cycles from a fighter load spectrum arranged as amplitude–exceedance curves [39]. Of the three different techniques used to count closed cycles, the Rainflow technique yielded the most severe exceedance curve. Considering the power relationship between fatigue damage rate and applied stress amplitude, the area enclosed between these curves indicates the potential for error in life estimate due to incorrect cycle counting.

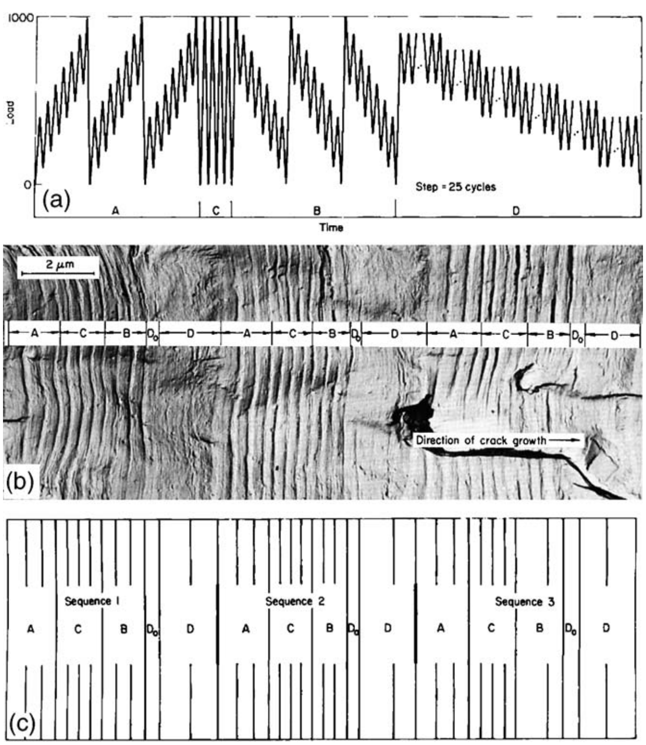

Fig. 9. Fractographic confirmation of the validity of the Rainflow cycle counting technique for fatigue crack growth analysis under spectrum loading [40]. Digitized striation bands from sequences A and B were compared with the arithmetic sum of striation spacing from their constituent cycles applied separately in C and D.

this possibility [40]. However, in the process of Rainflow cycle-counting, load history effects must not be overlooked. This is more readily accomplished in short duty cycle spectra, with cycles closing between the commencement and conclusion of a mission cycle. Load spectra involving extreme excursions embedding considerable growth from intervening cycles would call for incorporating sequential Rainflow.

Rainflow finds application in field data acquisition and fatigue testing and analysis under spectrum loading.

3.1. Field data acquisition

Embedded micro-processor based field data acquisition systems programmed with the Rainflow algorithm perform real-time analysis of load/displacement/acceleration input signals from one or more channels. Counted cycles are stored as a range–mean table of cumulative occurrences. While time-domain information may be lost in the process, the fatigue load content of the input load signal is stored in a compact format over practically unrestricted duration. For several years now, such devices are being used for health monitoring purposes on aircraft and aero-engines [41]. Similar devices are used for field data acquisition in ground vehicles, maritime structures and power machinery. The devices can be periodically milked to permit fatigue analysis or laboratory testing under simulated service conditions.

3.2. Fatigue analysis

Rainflow cycle count tables can be stored in non-dimensional form to serve as fatigue design inputs. Through duty cycle segmentation [42], Rainflow tables can be established for individual segments in an operational cycle. Their mix can be reconstituted as appropriate for a new operational or design requirement, avoiding the need to acquire a fresh set of field data and cutting down development cycle times. The compactness of data storage permits easy exchange of Rainflow tables in collaborative studies, irrespective of the duration of the constituent load spectrum. Their tabular format permits cumulative damage studies to distinguish between damage contribution of individual spectrum events. This is a valuable input for decision-making in the design stage (re-design to reduce impact of overloads, e.g. gust alleviation in aircraft) and also in the operational stage (e.g. aircraft rotation to ensure uniform utilization [43]).

3.3. Fatigue testing

On-line Rainflow analysis during spectrum load testing has several applications:

1. Iterative testing to determine closure and threshold

levels [44]. As shown by results in Fig. 10, repeat tests with incremental omission criteria may reveal material constants of direct application value to the spectrum and material in question. In these experiments, a flight-by-flight Rainflow analysis is performed and omission criteria are applied to counted (closed) cycles. Sequence effects as well as the effect of major cycles (even of small magnitude) in individual flights will be retained. The Rainflow algorithm will leave uncounted half-cycles in each flight ensuring that at least one major cycle (e.g. ground–air–ground) will remain in each flight (Fig. 10e).

2. If closure and thresholds are known, these can serve as crack growth-sensitive cycle omission criteria, leading to considerable acceleration of the test without compromising quality of test results.
3. Monitoring test quality. Emerging industry emphasis on documentation of the quality process calls for documentation of test quality. On-line Rainflow readily meets this requirement by recording the required and achieved Rainflow cycle counts in the course of a fatigue test. The process is applicable to both constant amplitude as well as spectrum loading and provides statistics that can be used to characterize deviations as well as compute their significance through cumulative damage analysis.

4. Concluding remarks

The Rainflow cycle counting process forms an integral part of any exercise involving spectrum loading. It is based on slip-reversal, which is the driving mechanism of the fatigue process. This underscores the importance and relevance of the technique.

Spectrum load fatigue brings out deviations in sig-

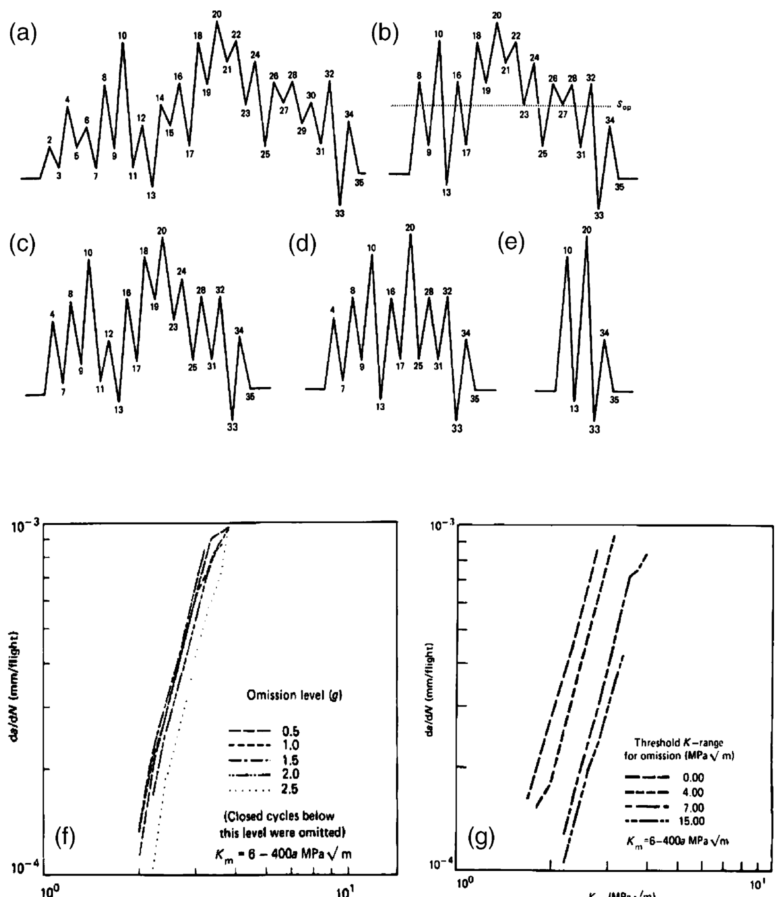

Fig. 10. (a)–(e) Schematic of the consequences of progressive omission of rainflow counted cycles from a single flight (duty cycle) [44]. (a) Original sequence. (b) Cycles below crack opening load omitted. (c)–(e) Cycles of progressively greater magnitude omitted. Sequence cannot be shrunk beyond (e) as what remain are half cycles that will not close. This feature of Rainflow ensures that extreme cycles in a duty cycle cannot be omitted—even inadvertently. (f,g) Show test results obtained using on-line Rainflow based spectrum editing in iterative testing with incremental omission levels. (f) Shows the consequences of omitting closed cycles below a given g-level. The crack growth rate results indicate that the crack was closed below 2 g. The maximum g-level in the spectrum was 9 g, indicating approximately 25% closure stress, which is backed up by direct evidence on closure. (g) Shows the consequences of omitting closed cycles below a given ΔK. These results indicate that omitted cycles would have contributed to crack growth, i.e., that even the smallest cycles carried ΔK greater than K_{th} [44]

nificant similarity criteria that under constant amplitude are uniquely related to ΔK and R and are therefore taken for granted. These criteria include crack front geometry (including tip radius, crack front orientation, branching and plastic zone size), crack closure and crack-tip stress state. The first two can be handled from strictly mechanics considerations. Recent research appears to suggest that the effect of crack-tip stress state (including residual stress) on fatigue is through moderation of environmental action. If this is indeed so, constant amplitude da/dN data would in a strict sense, not qualify for application to spectrum loading except in vacuum.

A salient feature of spectrum load fatigue is its remarkable reproducibility, even by comparison to constant amplitude conditions. This extends down to threshold growth rates and to short cracks at notches [45,46]. The infrequent high loads under service load conditions control notch root and crack-tip plastic zones and residual stress. These appear to even out micro-structure and defect geometry-related inhomogeneties in stress distribution in a manner that enforces highly reproducible damage (crack growth) due to the large number of small cycles in a load spectrum. One may conclude that our ability to predict spectrum load fatigue response is determined by our understanding of underlying mechanisms, their quantification and synergy, rather than by any 'vagaries' in material behavior. Extension of such knowledge to structural fatigue will have to address issues related to service load tracking and structure response including behavior of fasteners and joints. The nature of stress intensity variation in point load geometries (such as lug joints and riveted panels) is such that crack growth rates often remain more or less constant over the first few mm of growth [47]. As observed by Wanhill et al. [48], growth rates between crack size intervals of 0.03 –5 mm were remarkably similar, raising questions about the relevance of the so-called 'short crack' effect for fatigue of joints under spectrum loading.

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