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International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Strain Life Approach to Fatigue

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DOI: https://doi.org/10.55248/gengpi.4.623.43118

ABSTRACT-

Metal fatigue has been a problem for more than 150 years, but because of rapid developments in fracture mechanics analyses, possibly at the expense of the traditional approach based on cyclic deformation processes, a far better understanding of fatigue failure behaviour has recently been achieved. Consequently the engineer now has the basic tools at his/her disposal to make good assessments of the numerous factors that control the fatigue lifetime of engineering materials, components and structures. Additionally, more intensive interdisciplinary research studies involving chemists, materials scientists, mathematicians and physicists—but engineering led—have generated both greater insights into long-known industrial problems and routes to required solutions. This paper traces the growth of recent developments in understanding metal fatigue from the days of our mentors to the present day, and concludes with a brief review of some future research areas that are now available for exploitation.

Index Terms- *Metal, Fatigue Failure, Crack Initiation, Persistent Slip bands, Inclusions, grain boundaries*

1.0 INTRODUCTION

In materials science, **fatigue** is the initiation and propagation of cracks in a material due to cyclic loading. Once a **fatigue crack** has initiated, it grows a small amount with each loading cycle, typically producing striations on some parts of the fracture surface. The crack will continue to grow until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the fracture toughness of the material, producing rapid propagation and typically complete fracture of the structure.

Fatigue has traditionally been associated with the failure of metal components which led to the term **metal fatigue**. In the nineteenth century, the sudden failing of metal railway axles was thought to be caused by the metal *crystallising* because of the brittle

appearance of the fracture surface, but this has since been disproved.[1] Most materials seem to experience some sort of fatigue-related failure such as composites, plastics and ceramics.[2]

To aid in predicting the fatigue life of a component, fatigue tests are carried out using coupons to measure the rate of crack growth by applying constant amplitude cyclic loading and averaging the measured growth of a crack over thousands of cycles. However, there are also a number of special cases that need to be considered where the rate of crack growth is significantly different compared to that obtained from constant amplitude testing. Such as: the reduced rate of growth that occurs for small loads near the *threshold* or after the application of an *overload*; and the increased rate of crack growth associated with *short cracks* or after the application of an *underload*.[2]

If the loads are above a certain threshold, microscopic cracks will begin to *initiate* at stress concentrations such as holes, *persistent slip bands* (PSBs), composite interfaces or grain boundaries in metals.[3]

The fatigue failure of metals is often treated as the result of cyclic hardening/softening, crack initiation ,and crack propagation leading to final fracture. In flaw-free materials, a significant fraction of the total life time is spent before the first detectable micro cracks appear. For instance, the stage of the crack initiation takes up about 18–54% of the fatigue lifetime of nickel-based alloy. The number of cycles to failure increases linearly with increasing the number of cycles for the crack initiation, which is independent of the grain size and stress amplitude. At low amplitudes the initiation stage can occupy even the majority of the lifetime. At high amplitudes the initiation is usually accomplished within a small fraction of the fatigue life.[4]

Another fraction of the lifetime is needed for the propagation of the microstructurally small cracks to reach the size of the physically small cracks (i.e., cracks of the size about 0.1–1 mm). Quantitative description of fatigue propagation of physically small cracks and macro cracks (i.e.,cracks of the size of the order of millimeters and more) has been made possible based on macroscale approaches such as fracture mechanics based Paris law. Progresses have also been made in the description of the crack initiation process of various types of fatigue. However, the predictive models for the initiation of microcracks and following propagation of microstructurally small cracks have not yet been well established though many research efforts have been taken for decades. The aim of this paper is to offer an overview of present state of the fatigue crack initiation mechanisms/stages in metal materials. Further efforts in developing the physically based models are expected.

2.0 Review Of the Initiation Of Cracks In Metals

2.1 Crack Initiation at Persistent Slip Bands

In pure metals and some alloys, irreversible dislocation glides under cyclic loading usually lead to the development of persistent slip bands (PSBs), extrusions, and intrusions in surface grains that are optimally oriented for slip. The nature of the slip characteristics often dictates the surface topography near the crack initiation site. The evolution of dislocation structures has been investigated for a number of metals and alloys, such as Cu, Ni, Ti, and nickel-based alloys.

The processes responsible for the formation of PSB, extrusions, and fatigue cracks in surface grains are well described in the reviews by.[5][6] In general, planar slip is prevalent in materials with a low stacking fault, while wavy slip is more prevalent in materials with high stacking Fault energy. A typical example of the persistent slip bands and cracking morphologies is shown for monocrystal Cu in Figure 1.[7] As displayed in Figure 1(a) with the macroscopic morphology, the whole gage length of the specimen was filled with PSBs. The intrusion and extrusion on the surface can be seen more clearly from Figures 1(b) and 1(c) with high PSBs densely distributed in the center part of the gage length. As presented in Figure 1(d), the slip-band (SB) cracks form exclusively and preferentially in the monocrystal Cu specimen. Recent work on surface crack initiation from PSB has focused on the evolution of slip morphology with fatigue cycles.

For instance, experimental results of Ni 200 indicates that the slip bandwidth, spacing, and the width-to-spacing ratio vary with fatigue cycles and show substantial variations among individual grains during strain-controlled low-cycle fatigue .[8] The slip band width (h) and spacing (w), which are defined in Figure 2(a) and the slip morphology of is shown in Figure 2(b). There appears to be a linear relation between h/w ratio and number of fatigue cycles, N, in a slope of 0.168 in a double logarithm plot, as seen in Figure 2(c). Moreover, the slip bandwidth appears to be relatively insensitive to the strain amplitude.

However, the slip band spacing decreases with increasing the strain amplitude increased. At higher strain amplitudes (e.g., 70.75%), the slip band width and spacing are almost identical. Hence,the intensity and number of slip bands increase with the number of cycles, and the surface exhibits more and more marked notch-peak topography.

2.2 Subsurface Crack Initiation Models

Research efforts also focus on the transition of crack initiation from specimen surface to subsurface with the decreasing of load level, which is directly related to the shape of S–N curves. The occurrence of subsurface crack initiation, being competitive with the surface initiation mode, induces multi-stage S-N curves in either duplex or step-wise shape. The S–N curves can also show a continuously decreasing shape in some low strength steels up to the UHCF regime. Surface crack initiation is highly influenced by surface and environment conditions, while subsurface crack initiation is dependent on size, shape and location of micro-defects.[9][10]

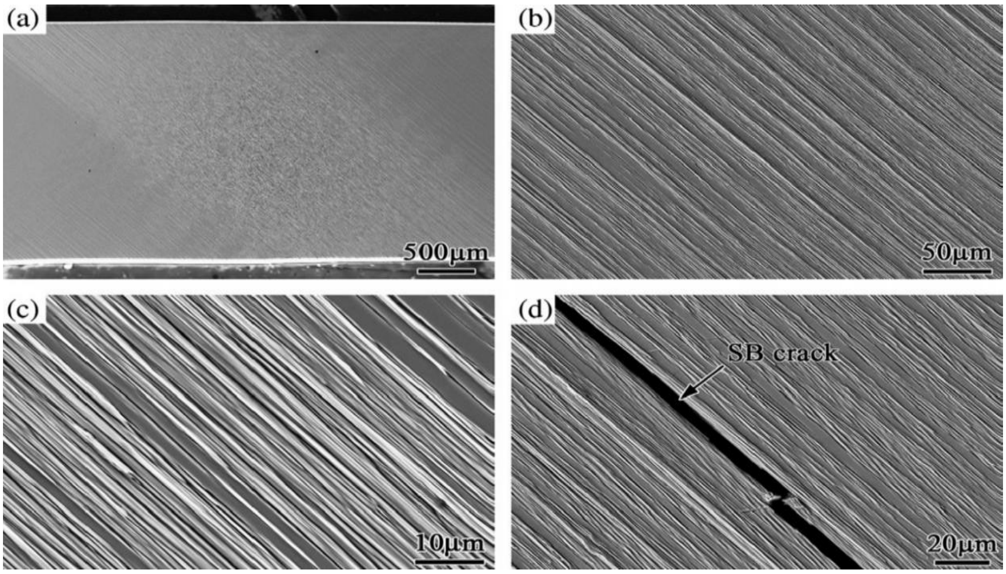

Figure 1 Images of the fatigued monocrystal Cu, (a) the macroscopic slip morphology with higher magnification showning (b) and (c), (d) the typical SB crack. The numbers of cycles required to the initiation of fatigue cracks monocrystal Cu is1.8 x 10^5. Quoted from.[7]

[11] discussed that such conditions as oxidation layers formed at high temperature and compressive residual stress at specimen surface are effective to promote the transition of crack initiation from surface to subsurface or interior micro-defects.

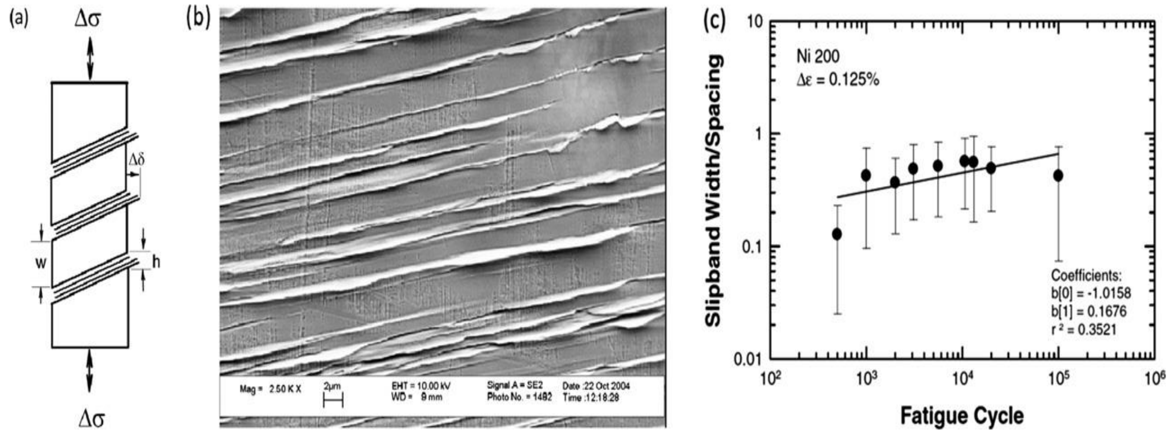

Figure 2 Evolution of slip bandwidth and spacing of Ni200 during low-cycle fatigue: (a) schematics of slip bandwidth and spacing in an individual grain, (b) surface micrograph showing PSB in a surface grain in Ni 200, and (c) ratio of slip bandwidth-to-spacing as a function of fatigue cycles for Ni 200 tested at strain amplitude of 0.125%. Quoted from [8].

2.3 Crack Initiation at Grain Boundaries

Initiation at grain boundaries is also conditioned by the cyclic slip processes. The first microcracks at grain boundaries (GBs) and twin boundaries[12] can often be observed as the result of slip impingement. General, fatigue cracks initiate at GBs or TBs where impinging slip causes plastic incompatibility and stress concentration. Furthermore, GB initiation is more prevalent at high-strain fatigue than at low-strain fatigue. For Ni200, the tendency of GB cracking relative to SB crack was reported at several strain amplitudes.[5] It was found that the percentage of fatigue cracks formed a long slip bands decreased and the cracks formed at the GBs increased with increasing the strain amplitudes. Intergranular cracking from GBs accompanied by PSBs is an important fatigue damage mode in polycrystals and bicrystals during cyclic deformation. It has been recognized that PSBs due to the overall plastic strain was often terminated at the large-angle GBs, as seen in **Figure 3** for coaxial copper bicrystals.[13] Different factors, such as grain size, GB structure,the misorientation between neighboring grains, have important influences on the fatigue crack initiation GBs. It has been recognized that there exists a great difference in the fatigue damage mechanisms between bicrystals and polycrystals, which can be mainly attributed to the effects of GBs and the crystallographic orientations. Intergranular fatigue cracking strongly depends on the interactions of PSBs with GBs in fatigued crystals, rather than on the GB structure itself.

A large body of theoretical and modeling work has been focused on predicting the resistance to slip transfer using boundary related parameters. Among the proposed models, the model proposed by [14] to predict the stress concentration as a result of SB–GB interactions, has been widely used.

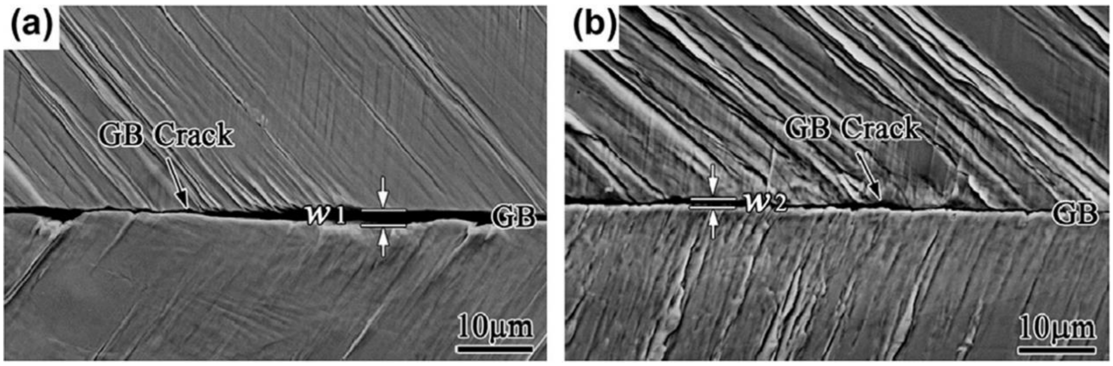

Figure 3 Fatigue cracks initiated from GBs for copper bicrystals. Quoted from.[13]

The GB cracks are prone to initiate at high-angle grains. The initiation site may be located in a cluster of grains with similar crystallographic orientation that enables easy slip transmission across low-angle grain boundaries. Such a grain cluster also acts like a single grain with an effective slip distance that is larger than the average grain size. The implication is that local texture is important for crack initiation and its influence can manifest as a neighborhood effect by adjacent grains. [15][16] constructed a model for prediction of fatigue crack initiation in Udimet720 wrought Ni-based super alloy based on the material's microstructure. The energy of a PSB was monitored and an energy balance approach was taken, in which cracks initiate and the material failed due to stress concentration from a PSB which can traverse low-angle GBs. As a consequence of the ongoing cyclic slip process, the PSBs evolved and interacted with high-angle GBs, resulting in dislocation pile-ups, static extrusions in the form of ledges/steps at GB, stress concentration, and ultimately crack initiation.

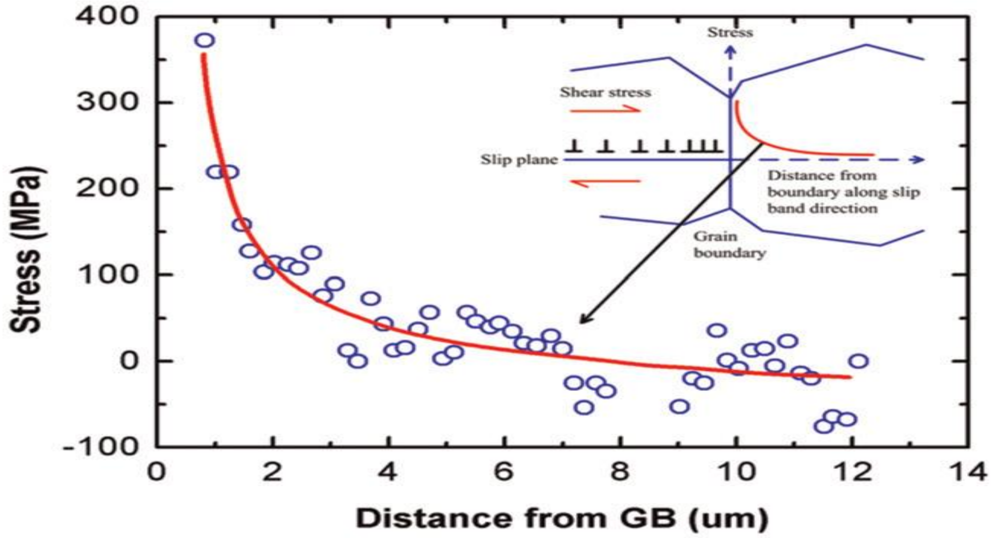

Figure 4 Stress concentration ahead of the blocked slip band with comparison to the model described by [17]

2.4 Crack Initiation at Inclusions

As for fatigue crack initiation at surface inclusions, this situation mostly occurs in materials with large enough particles.For example, experimental investigations of a nickel-based super alloy GH4169 show that fatigue crack initiation mechanisms were dependent on the grain size. Fatigue cracks preferentially initiated at the second-phase particles for the specimens with relatively small grain size, i.e., 9 mm, but they tended to initiate at grain boundaries for the specimens with 25 mm grain size. There was a transition of fatigue crack initiation mechanism between fine grain size and coarse grain size. The reason that fatigue cracks preferentially initiated at the second-phase particles can be attributed to their low toughness comparing with the matrix. Hence, second-phase particles were generally more easily broken and serve as stress concentrators than the bulk material. However, the strength of the bulk material decreased and the plastic strain within the grains increased with increasing the grain size. In such a case, fatigue cracks tended to initiate at the fatigue slip bands and the grain boundaries.[4] At high temperature, the second-phase particles which located at the surface of specimens are easily to be oxidized, leading to their volume expansion. The residual stresses caused by the oxidation could be big enough to induce fatigue crack initiation at oxidized particles. From the replica micrograph shown in Figure 5, fatigue crack is clearly seen to initiate around a second-phase particle at 650^0C. The similar phenomena can be found in other corrosion fatigue tests in high-temperature water. [18]

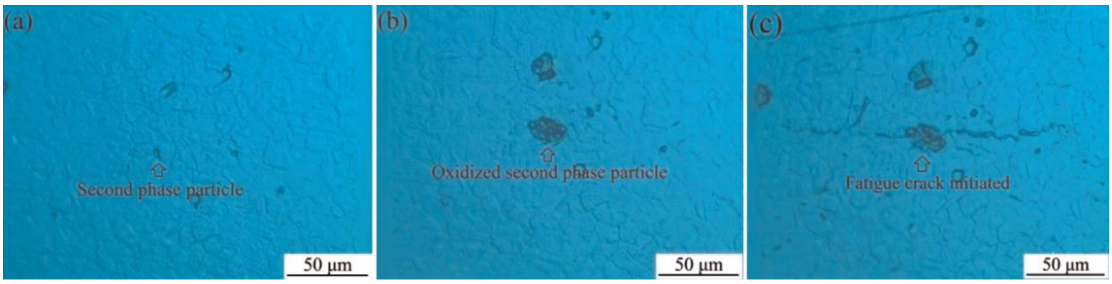

Figure 5 Replica micrograph of fatigue crack initiation of nickel-based super alloy GH4169 at 650^0C, (a) replica before fatigue testing, (b) replica after 13000 cycles, and (c) replica after 22500 cycles.

Fatigue crack initiation at internal inclusions or particles hard particles is often observed in steels, Al alloys and Ni-based alloys. In general, larger inclusions concentrate higher plastic strain and lead to a lower fatigue crack initiation life. Similarly, the local plastic strain increases with increasing number of inclusions. For instance[19] developed a microstructure-based fatigue modeling approach which recognizes multiple inclusion severity scales for crack formation in high cycle fatigue (HCF) of cast Al–Mg–Si alloy. The model addresses the role of constrained micro plasticity around debonded particles or shrinkage pores in crack formation. The transition from HCF to low cycle fatigue (LCF) is shown from computational micro mechanics to be associated with the percolation limit of cyclic micro plasticity within the eutectic regions. For Ni-based disk alloys, the fatigue crack initiation sites are obviously influenced by the ceramic inclusions or pores.[20] determined the effect of preexisting defects on the strain-controlled fatigue crack initiation process at elevated temperature and room temperature of two high strength P/M nickel-base super alloys. In most cases, particularly at elevated temperature, the initiation process was associated with a large pre-existing defect, either a pore or a non metallic inclusion. There was a tendency for surface initiation at high strain ranges but interior initiation at lower strain ranges. However, stage I crystallographic cracking at or near the surface dominated the process in all strain range regimes at room temperature, This difference was attributed to the differences in deformation mode for nickel-base super alloys at room and elevated temperature. Similar observations were also reported for Rene 88 and Rene 95 Ni- based alloys with seeded inclusions.

2.5 Phases of Crack Growth

It is generally accepted that the process of crack growth under cyclic loading is divided into three phases (Figure 6)[21]: crack initiation, crack propagation, and structural fracture. Specifically, the first stage presents a threshold, below which there is no crack growth. The second stage shows a relatively steady state, in which the crack growth rate increases steadily with the increasing number of cycles (this is always described by Paris' Law [22]). The final stage represents an unstable situation, where the engineering structure fails within a small number of cycles.

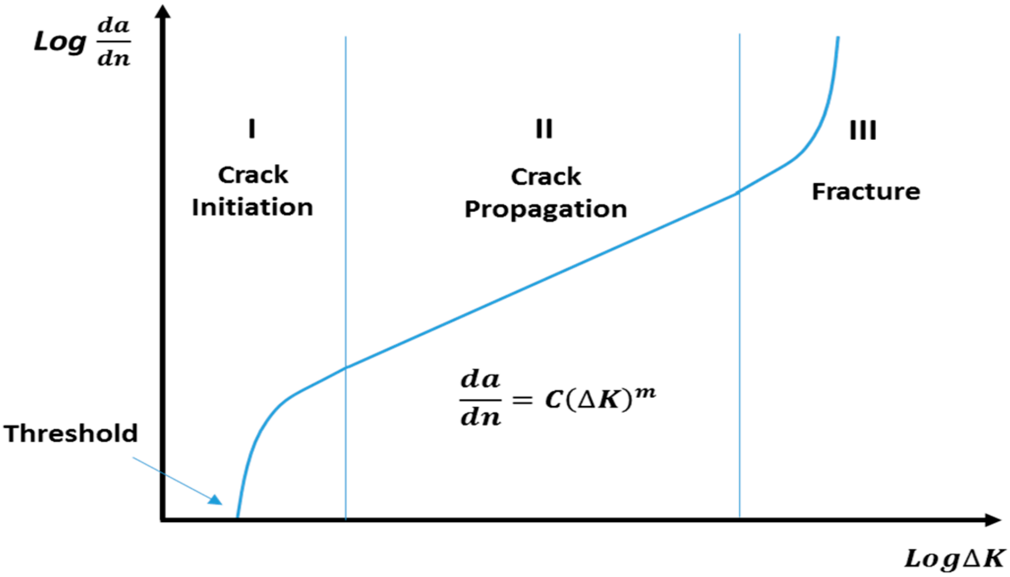

Figure 6. Three stages of crack growth.

After the process of micro-crack initiation, the localized stress is highly concentrated at the crack tip, which then recruits more vacancies from the bulk of the grain, and these are diffused to the crack tip along the grain boundary. This leads to further propagation of the creep crack along the grain boundary. High temperature provides more favourable conditions for diffusion behaviour, hence advances the creep crack along grain boundaries. Thus, creep failure is strongly temperature dependent.

Overall, crack-growth behaviors of fatigue and creep follow different principles; specifically, fatigue effect occurs via cracks through the grains, while the creep effect involves fracture along the grain boundary.

Significant research effort has been exerted to explore the crack-growth path, through performing fatigue tests and observing the fracture surfaces (fractography). These research efforts mainly focus on the specific features of crack growth for fatigue or creep, such as the creep damage caused by triple points [23,24,25] and grain-boundary effects for fatigue-crack growth [26,27].

In summary, this literature proposes multiple mechanisms at the microstructural level to describe the crack-growth process.

2.6 Stage I: Crack Initiation

The first stage (stage I) is that of crack initiation. The crack initiation mechanics is summarized as follows. Fundamentally, crack initiation is caused by stress concentration, where two situations are presented. A typical situation is that the crack starts at a surface defect such as a machining mark. This provides a highly localised stress concentration, hence a pre-existing micro-crack [21]. By this means, a crack is initiated at this specific point, and then the localized plastic strain caused by the ductile micro-tearing events provides opportunity for further propagation.

Second, for a situation with perfect surfaces (defect-free), dislocations play an important role [28] for the initiation of a fatigue crack [29] (Figure 1 therein), [30] (Figure 1 therein). During this process, loading cycles cause dislocations to pile up at the microstructural level. These dislocations are in the crystal lattice at the nanoscale. Under loading, they align and coalesce to produce thicker slip planes through the crystal and eventually slip bands at the macrostructural level [31]. Under cyclic loading, there is more relative movement between the bands, so the effect becomes more pronounced—the bands are further displaced. We suggest that this is due to irreversibility caused by the localized hardening effects of the dislocations.

In the area of persistent slip bands, the slip planes extrude or intrude to the surface of the object, see **Figure 7**. This results in tiny steps in the surface, where the stress concentration then results in crack nucleation.

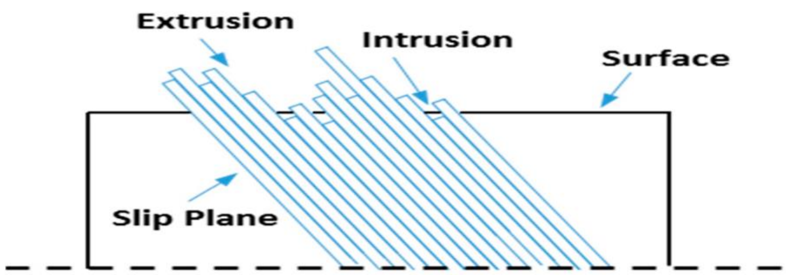

Figure 7. Crack initiation due to dislocation.

In stage I (the crack-initiation stage), a crack-growth threshold exists. In general, there are two types of thresholds [32]: microstructural and mechanical. The microstructural threshold describes the initiation of micro-cracks at different microstructural features, such as slip bounds and cavities. The mechanical threshold is related to macroscopic geometry for long crack growth, and is discussed in the present work. Below this latter threshold, there is ordinarily no crack growth [21]. We attribute this to the cracks being too short to result in a meaningful stress concentration effect (which is primarily an effect of proportional geometry). Also, if there are many superficial defects at the surface—which is usually the case—then the material does not have a geometrically exact boundary at the nanoscale, and hence the stress avoids this region: the many small defects effectively decrease the stiffness of the superficial layer, and hence this layer is to some extent unloaded.

On the one hand, this process is attributed to the concept of strain energy release rate, which describes the energy consumed per unit of newly created crack surface. This implies that the more strain energy is released, the more new crack surfaces are produced. Normally, the strain energy release rate could be numerically related to the M-integral [33,34]. The relationship between the number of cycles and M-integral was investigated by Margaritis [35] where the M-integral increases with the increasing number of cycles at the early phase, then it decreases over the peak, and finally it reaches a constant situation. This trend is consistent with observation of the initiation stage shown in **Figure 6**. Specifically, after the threshold, increased energy (released strain energy) accelerates the increase of crack-growth rate at the beginning phase, then reduced energy retards the acceleration of the crack-growth rate, and finally a steadily increasing crack-growth rate is achieved under a situation with constant energy (this is viewed as the crack-propagation stage).

An alternative explanation is that the unstable behaviour of crack growth in stage I is due to shear mechanisms [36,37]. Generally, a crack is propagated through two different methods: the plastic deformation around the crack tip and the shear-stress effect at the planes oriented at 45° to the loading direction. During the initial phase of crack growth, a small plastic zone and a small stress field are presented around the crack tip because of the small magnitude of stress intensity. In this case, the mechanism of plastic deformation around the crack tip may not be significant enough to become the driving force for crack growth. Instead, the shear stress at the planes oriented at 45° provides more favourable conditions for crack growth. This is because the shear stress at these planes and the relative movements between these planes under cyclic loading provide more vulnerable areas for crack growth. Prior damage and lattice imperfections may exist on these planes from previous loading cycles. In this case, a crack grows along the planes oriented at 45° with a minimum of effort, hence resulting in a high acceleration of the crack-growth rate.

As the stress intensifies, the shear-stress effect is gradually suppressed by the plastic-deformation mechanism; hence, the acceleration of crack-growth rate is reduced. This is because, during this process, the direction of the crack growth gradually deviates from the surface of the planes oriented at 45°, and then the behaviour of penetrating the grain boundary results in the deceleration of crack-growth rate. Finally, crack-growth behaviour is stably caused by the crack-tip plastic zone, and a steady situation is achieved (stage II is initiated).

2.7 Stage II: Stable Crack Growth

A crack nucleated in first stage may be propagating or non propagating type depending upon the fact that whether there is enough fluctuation of load or not for a given material. A fatigue loading with low stress ratio (ratio of low minimum stress and high maximum stress) especially in case of fracture tough materials may lead to the existence of non propagating cracks.

However, growth of a propagating crack is primary determined by stress range (difference of maximum and minimum stress) and material properties such as ductility, yield strength and microstructural characteristics (size, shape and distribution of hard second phase particle in matrix). An increase in stress range in general increases the rate of stable crack growth in second stage of fatigue fracture. Increase in yield strength and reduction in ductility increase the crack growth rate primarily due to reduction in extent of plastic deformation (which reduces blunting of crack tip so the crack remains sharp tipped) experienced by material ahead of crack tip under the influence of external load. Increase blunting of crack tip lowers the stress concentration at the crack tip and thereby reduces the crack growth rate while a combination of high yield strength and low ductility causes limited plastic deformation at crack tip which in turn results in high stress concentration at the crack tip. High stress concentration at the crack tip produces rapid crack growth which reduces number of fatigue load cycle (fatigue life) required for completion of second stage of fatigue fracture of component.

All the factors associated with loading pattern and material which increase the stable crack growth rate, lower the number of fatigue load cycle required for fracture. High stress range in general increases the stable crack growth rate. Therefore, attempts are made by design and manufacturing engineers to design the weld joints so as to reduce the stress range on the weld during service (of possible) and lower the crack growth rate by developing weld joints of fracture tough material (having requisite ductility and yield strength).[38]

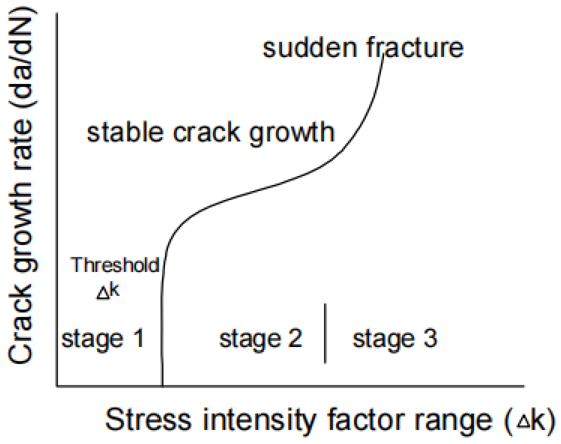

Fig. 8 Stage II stable fatigue crack growth rate vs stress intensity factor range in fatigue test.

The second stage (stage II) shown in Figure 8 presents the behaviour of crack propagation, wherein the crack growth undergoes a relatively steady process. This stage is numerically presented by Paris' Law (Equation (1))[22], which shows a power-law relationship between the crack growth rate and the range of the stress intensity factor during the fatigue cycle:

$$\frac{da}{dn} = C(\Delta K)^m \qquad (1)$$

where *da/dn* is the crack growth rate; Δ*K* is the effective stress intensify factor, which is identified as the difference between maximum and minimum stress intensify factors for one cycle; *K* is the stress intensify factor; *a* is the crack growth; *n* is the number of cycles; and *C* and *m* are constants.

The crack-growth process of creep fatigue is mainly discussed under the second stage of crack growth, and this discussion is based on the idea of the plastic blunting process. [39]

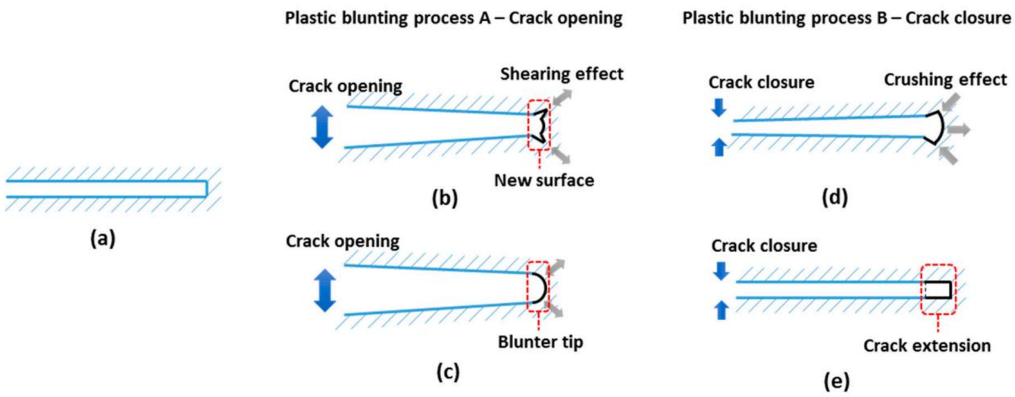

Figure 9. Plastic blunting process

2.8 Stage III: Structural Failure

In this stage, crack growth rate increases rapidly, and part separation commences when the total crack length reaches a critical value (final fracture). this stage represents an unstable state where the equilibrium shown in the second state of crack growth is broken due to intensified accumulation of damage and cross sectional area. This is attributed to high stress field at the crack tip due to high stress intensity[37]; hence the plastic zone becomes large compared to the crack size

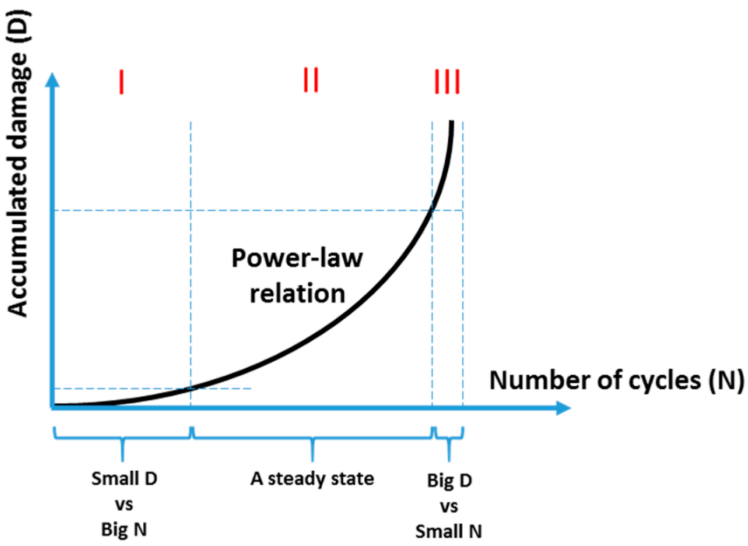

Figure 10. Damage Accumulation

During the process of crack growth, the creep-fatigue damage gradually accumulates with the increasing number of cycles, and this process is presented in a power-law relation. The idea of the crack tip plastic zone implies that the stress concentration around the crack tip plays an important role in crack growth. Specifically, the more the stress is concentrated, the larger the plastic zone, and then the more the crack is promoted. Therefore, we assume that crack growth is a geometry-related behaviour, and the crack growth rate (crack growth in one cycle) may be related to the size of the plastic zone. Normally, the area of a zone can be presented as a second-order power relation with a certain dimension, such as radius for circle and the length of a side for square. In this case, since the stress amplitude is directly related to size of the plastic zone, we believe that the applied loading could be related to the crack growth rate in a power law form. In addition, this relation is also consistent with the idea of damage accumulation shown in Figure 10. In the first stage, the original steady state (a perfect body) is suddenly broken due to the large amount of accumulated energy, which implies at this stage a small amount of damage is produced with a large number of loading cycles (stage I in Figure 9). Then, after the process of rebalancing, the damage accumulation gives a relatively steady state, where the rate of accumulation stably increases (stage II in Figure 9). Finally, when the total damage reaches or is close to a critical value, the load-bearing capacity collapses in a short time. This stage implies that much damage is produced within a small number of loading cycles (stage III in Figure 9).

3.0 Summary Of The Crack Growth Process and Mechanisms

In the present work, a microstructural graphical-based model for creep fatigue is proposed. In this microstructural conceptual framework, we propose that different crack growth mechanisms are active for different stages in the temporal evolution of the crack (stages I to III), different parts of the tension-compression cycle, and for different regions within the microstructure (grain boundary, triple point, inside the grain). In general, the temporal evolution of the crack is mainly based on the mechanisms of the plastic blunting process, stress-concentration state and diffusion-creep behaviour. The illustration of the crack-growth process is presented in three different stages:

3.1 Stage I: Crack initiation

In the first stage (the crack initial stage), a threshold is presented, below which no significant crack is detected. The existence of this threshold can be attributed to the effect of stress concentration. For a surface with defects (such as a machining mark), the stress concentration is caused by the pre-existing micro-cracks. For a defect-free surface, the behaviors of extrusion and intrusion between slip plans give some tiny steps in the surface, which then results in the stress concentration.

3.2 Stage II: Crack propagation

In the second stage (the steady stage of crack growth), the crack-growth behaviors under tensile loading and compressional loading were discussed separately. The primary differentiating factor between the tension-compression cycles can be explained by the plastic blunting process. Specifically, tensile loading creates a new crack surface due to the shearing effect around the crack-tip area, and then the crushing effect results in crack extension (by maintaining the new surface created by the tensile loading) under the compressional loading. Regarding the microstructure, the plastic blunting process implies that the damage produced within one tension-compression cycle is not a reversed process since the atoms cannot return to their original positions after one cycle. In addition, the crack-growth behaviors of fatigue and creep were also illustrated separately. Specifically, the fatigue component was generally presented by the plastic blunting process shown above, and the creep component was explained by the mechanism of diffusion creep. On the one hand, stress concentration at the crack tip provides a favourable condition for diffusion to form voids due to the stress-gradient effect, and then the void coalescence by shearing of the bridges between voids results in crack growth. On the other hand, diffusion creep gives grain elongation under tensile loading, which then further opens the crack created by fatigue effect. In addition, grain elongation also gives the shear stress at the grain boundaries between two adjacent grains, which probably results in the mismatch behaviour of the crack due to weak atomic bonds at the boundaries; then, the crack widens. Furthermore, the crack-growth behaviour with respect to the grain-boundary effect was discussed, and this effect plays a more important role in creep-crack growth than fatigue behaviour. In this case, due to the shear stress between two adjacent grains caused by grain elongation, the grain-boundary effect results in a blunter crack tip or wider crack body (mismatch). In particular, this effect can be presented by a special situation, the triple-point effect. In the triple points, the high stress concentration provides better conditions for diffusion.

3.3 Stage III: Structural failure

In the final stage (structural failure), the fracture occurs within small loading cycles. This can be attributed to the high stress field at the crack tip. Specifically, under this stress state, the plastic energy exceeds the needs for producing the new crack surface. In this case, a part of energy is applied to create the new surface, and the rest of the energy is applied to form voids, which further promote crack growth through internal necking.

ACKNOWLEDGEMENT

The author wishes to thank Professor M. A. Hassan, Engr. Shahid M. Dodo, Engr. Aminu Baba, Engr. Shehu Abdulhamid and Engr. Umar Faruk Bakari, all of which without their contributions, this work would not have been possible.

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