ON THE MECHANISM OF CYCLIC CRACK PROPAGATION IN AA2024 T3 ALLOY

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Abstract: Fatigue crack growth in aluminium alloys is strongly affected by the applied loading conditions that have a strong effect on measured growth, which is generally subject of prediction models. To improve predictive capabilities, the effect of cyclic loading on the microscopic mechanisms of crack tip formation and its closure should be thoroughly understood. To that aim, past literature proposed various models to explain fracture surface observations, that seemingly partially disagree with each other. In the current study, fatigue crack growth experiments were performed employing a crack tip freezing method to consolidate the crack tip state in particular moments of load cycles. The observed features are striations and their shape, surface ridges and fissures. Through observations a comprehensive mechanistic model is proposed that explains the observations presented, and explain why current state of art models in certain circumstances come to apparent different explanations.

Keywords: Crack growth, Aluminium 2024-T3, Constant amplitude

INTRODUCTION

In most cases, the fractographic analyses of tested and serviced components cover cracks in stage II (Paris regime), with the fracture surfaces containing striations and arrest marks as the most characteristic surface features associated with cyclic crack growth. To interpret the crack growth on a cycle-by-cycle basis, many existing mechanistic models can be employed. Unfortunately, the numerous available mechanistic models contradict each other, even when the same alloy is considered. Depending on the specific model adopted, misinterpretation of the crack growth process and of the formation of analysed fracture surfaces can occur.

It is well established that crack growth in stage II is a result of the competing intrinsic growth mechanisms occurring at and ahead of the very crack tip, and of the extrinsic crack growth retardation mechanisms taking place in the crack wake [1, 2]. The existing mechanistic models are essentially intrinsic mechanism models; extrinsic mechanisms are not considered to alter the fracture surfaces in systematic manner. Most intrinsic crack growth models assume that either (i) localized shear off deformation take place at the crack tip during the application of tensile load excursion [3-8] or (ii) that the formation of new crack tip is governed by homogeneous plastic deformation [9-11]. The formation of sharp crack tip with V-shaped profile is assumed to occur under localised shear deformation, while formation of semi-circular, U-shaped profile is assumed to occur in homogenous plastic deformation. In addition to this difference, models differ also regarding the behaviour during the load reversal. One group of models proposes that the closure of the newly formed crack tip profiles will start at the very crack tip apex and will progress towards the back of crack tip profile [4,8,12,13]. Another group of models proposes that the direction of the reversed slip and the closure of the crack tip will initiate at the back of the crack tip and the closure will gradually progress towards the very tip of the crack [3,7,9,10]. The combination of the crack tip opening and closure geometries and deformation characteristics in a particular model is used to explain the formation of either ductile striations with convex or concave profiles (type A), brittle striations with flat profiles (type B) or mixed mode surface striations with more complex profiles [14]. Theoretically, combination of all considered striation types that could be formed on the directly mating fracture surfaces can produce the configurations with either complementing (concave-concave, convex-convex) or mirrored (convex-concave) profiles. The variety of potential striation profiles that could be formed by the passage of the crack growth under cyclic loading is staggering and requires a deeper understanding.

Another feature commonly observed on fracture surfaces are surface fissures. Surface fissures are surface discontinuities left on the fracture surfaces. Those features separate individual striations from each other, allowing the identification of striations on the fracture surface during the analysis. Surface fissures do not seem to form in vacuum or in dry air [12], which makes the identification and the study of the crack growth on cycle-by-cycle basis more or less impossible in these conditions. For this reason, the understanding of the mechanisms governing the formation of surface fissures during crack growth are of high interest for researchers and engineers. As such, the formation of surface fissures is an integral part of numerous crack growth models. In one group of models, the surface fissures are assumed to be formed at the bases of newly formed crack tip flanks during the application of tensile load excursion due to the excessive shear slip process [4,12]. In another group of models, the surface fissures are formed at the very crack tip during the application of compression load excursion as a consequence of imperfect reverse plastic deformation or the inverse buckling process [9].

In all models mentioned until now, only the simplest cyclic loading sequences possible –Constant Amplitude (CA) loading– was considered. However, real-life structures are inevitably subjected to more complex loading conditions, such as Variable Amplitude loading and Multi-axial loading. If the behaviour of cracks growing under the simplest loading conditions cannot clearly established, elaboration on more complex conditions is currently not possible, leading to incorrect predictions. It is then paramount to achieve a definitive understanding of CA crack growth mechanisms, before tackling real-life complex loading conditions. Thus, in order to improve the understanding of the crack growth behaviour under the CA loading cycles in ductile 2024-T3 alloy, an experimental procedure is used in which the crack tip profiles are “frozen” (terminated) at desired level of tensile or compression load levels. The typical fracture surface features formed in the crack tip wake are then investigated through fractography. The combination of information obtained from these two approaches is finally used to develop a proper crack growth model, which combines intrinsic crack growth and extrinsic crack retardation mechanisms.

EXPERIMENTAL WORK

The objective of this study is to improve the understanding of mechanisms governing the growth of fatigue cracks at cycle-by-cycle level. A fractographic study was performed in order to characterize the occurrence of typical surface features. The geometrical changes, occurring at the very crack tips during the application of tensile and compression load excursions were also studied via employing so called “freezing” load sequences. The combination of information led to new insights that are presented in this section and discussed in the following section.

Test procedure - Test specimens

Flat, hourglass shaped specimens, containing the starter notch, were machined from AA2024-T3 sheets. Geometry and relevant dimensions are shown in **Error! Reference source not found.**. The orientation of the starter notch and the crack propagation is in the LT plane. The combination of the geometry of the specimen and of the size of the starter notch (machined using electro discharge machining) gives an initial stress concentration equal to 5.54 [15].

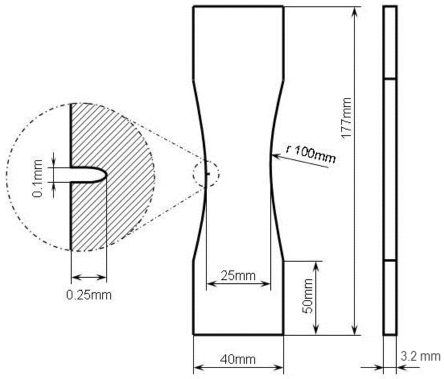

Figure 1: Geometry of the specimen used in testing program.

Test procedure – Loading sequences

CA loading sequences were used to produce the fractured specimens for the fractographic studies with the goal to characterize the formation of typical fracture surface features such as evolution of fracture surface roughness, orientations of local fracture planes, appearances and profiles of surface striations and position and shapes of surface fissures. Load cycles with a maximum applied loads resulting in a gross stress of 200 MPa and a stress ratio of R = 0.5 were applied; loading frequency of 10 Hz was used in this study.

Load sequences containing the “frozen” tensile and compression load excursions were used to investigate the geometrical changes occurring at the newly formed crack tips. In this case, CA load sequences having identical parameters as the load sequences used in the earlier mentioned fractographic studies, were applied on the specimens in order to initiate and grow the crack. The evolution of cracks was monitored at the surfaces of tested specimens with a travelling microscope until cracks reached the length of 3.5 mm. Previously gained experience showed that at this crack depth, satisfyingly large surface striations and surface fissures are formed, providing fractographic features for this study. To produce the “frozen” crack tip profiles, CA loading sequences were terminated and a load sequence containing “freezing” (terminating) load excursions were subsequently applied. These “freezing” load excursions were CA load cycles with small stress amplitudes (equal to 10MPa), applied in order to grow the crack deeper into the specimens. The application of the CA loading sequence with small stress amplitudes are assumed to not disturb or cause plastic deformation of the previously formed surface features. In this report, the most relevant results obtained from tests utilizing relative 50% and 100% tensile and 50% compression loads excursions will be presented and discussed. The graphical representations of used loading sequences and typical fracture surfaces are shown in Figure 3.

Test procedure – Fractography

A JEOL JSM7500F scanning electron microscope with secondary electron detector was employed in the fractographic and stereographic investigations performed on the tested specimens. In this investigation, the post-processing of the fractographic images was performed via commercially available program MeX developed by company Alicona Imaging GmbH [16]. The program automatically identifies the matching points on pixel-by-pixel level, and it performs trigonometric calculations determining the height dimensions. The working distance, pixel size and stage tilting angle input parameters were determined manually.

Formation of striation and fissures with their characteristic shapes and profiles

The brittle-like fracture surface facets with characteristic feather-like patterns were formed near the starter notch and up to the crack depth of approximately 1 mm. Minute surface ripples, possibly surface striations, and small surface micro cracks, were also observed on the same fracture surfaces.

Distinctly formed striations could be identified at the crack depth of ~1 mm ($\Delta K = 6.3$ MPa√m); surface striations with two different appearances were formed. In the first case, striations with smooth and featureless surface textures, separated from each other with narrow but distinctly formed surface fissures

(troughs), were formed. In the second case, surface striations that appeared to be covered with minute surface ripples were formed, separated from each other with wider but somehow less pronounced or shallower fissures. On the directly mating fracture surfaces, pairs of featureless striations or pairs consisting of featureless and rippled striations were formed. In general, striations at this crack depth appeared to be relatively shallow or with low spatial profiles. Surface striations with measurable spatial profiles, resembling convex shaped profiles, were formed at crack depths of ~1.5 mm ($\Delta K = 7.8$ MPa$\sqrt{m}$, Figure 2-A). Striations with pronounced convex or deformed convex profiles were observed on both directly mating fracture surfaces at the crack depth of ~2 mm ($\Delta K = 9.2$ MPa$\sqrt{m}$, Figure 2-B). In general terms, the positions of peaks and fissures formed on one fracture surface matched the positions of the same on the mating surfaces.
The fracture surfaces with increasingly wavier and complex profiles were formed at the crack depths of ~3 mm ($\Delta K = 11.8$ MPa$\sqrt{m}$, Figure 2-C) and larger, consisting of local fractures planes with variously tilted orientations on which the striations were observed. Striations with the characteristics similar to those formed at the shorter crack depths were formed on the fracture planes having rather modest tilts. On more tilted planes, striations with more complex shapes were formed, showing more extensive rippling and overall apparent plastic deformation patterns. Wider, and what appears to be more open surface fissures, separating the individual striations were also formed on the same local planes. At larger crack depths, the variation of the striation's size (spacing) along the same crack front become apparent; often, striations with various sizes could be seen on the very same crack plane. On directly mating fracture surfaces, striations with rather dissimilar textures, deformation patterns, apparent shapes, sizes and positioning of surface fissures were formed. The 3D spatial reconstruction of directly mating fracture surfaces revealed that in all cases, ductile striations with convex profiles (Type A) or mixed mode striations (deformed Type A) were formed, regardless of their apparent profiles or surface textures as observed during the fractographic study, being 2D projection views.
The general fracture surfaces became significantly wavier and irregularly shaped at crack depths of ~5 mm ($\Delta K = 17.2$ MPa$\sqrt{m}$) and at greater crack depths. Striations formed on local surface planes also showed to be of increasingly more complex shapes and surface textures and with more pronounced spatial (convex-shaped) profiles. Increased asymmetry (appearance and spacing) was also observed between striations formed on directly mating fracture surfaces.

Secondary cracks with out of plane orientations were also frequently observed on the fracture surfaces, progressively increasing in size along the increasing crack depths. These cracks were formed on one side of the crack, seemingly not altering the directly mating side in any way. The secondary cracks were formed under various oblique angles with respect to the general fracture surface plane and directions. In the case of forward directed cracks, secondary cracks showed to have rather significant impact on the general fracture surface appearance, causing the fracture surfaces to be considerably distorted. Surface striations formed in the vicinity of these cracks showed to be ill-shaped and severely deformed, especially at crack depth of ~3 mm and larger. The faces of forward oriented secondary cracks themselves were often covered with medium-sized surface ripples that resembled the appearances of surface striations. In the case of backward directed cracks, secondary cracks appeared to have only localized and rather limited impact on the general fracture surface appearance. Secondary cracks with backwards orientations seem to form sort of step- or ridge-like surface feature; in some cases, the extrusion-like features, covered with minute surface ripples, were also formed on the secondary crack, especially at larger crack depths. Secondary cracks appeared to be partially formed alongside the surface fissures separating individual striations from each other and partially under oblique angles with surface striations. When crossed, the secondary cracks appeared to cut through the surface striations. The directly mating fracture surfaces appeared to be unaffected and undisturbed by the deformation caused by secondary cracking.

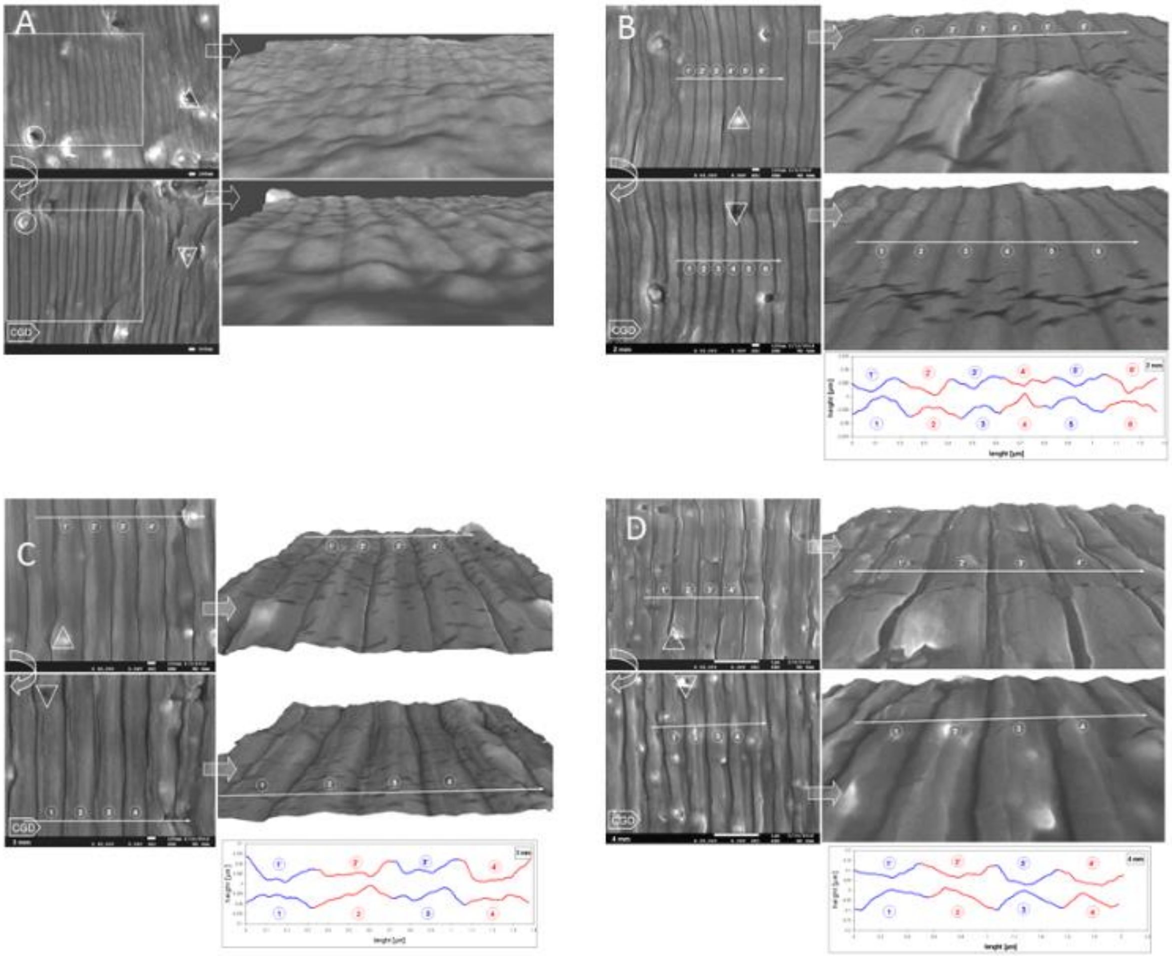

Figure 2: Typical fracture surface appearances containing convex striations at directly mating crack sides. Profiles corresponding to crack depths of (A) 1.5mm, (B) 2.0mm, (C) 3.0mm and (D) 4.0 mm.

Crack tip geometries

The most relevant results obtained from the studies on the crack tip profiles formation under frozen tensile and compression load excursions is presented in this section. The crack tip profiles appeared to be strongly dependent not only on the level of applied load excursions, but also on the position along the crack front and the tilting orientation (orthogonal vs. tilted) of the local surface planes on which the crack was formed.

The overview of fracture surfaces formed by combination of base CA sequence (100 MPa stress amplitude) with frozen tensile and compression load excursions, and by CA sequences with the stress amplitude of 10 MPa are shown in Figure 3. Fracture surfaces formed after surface ridges showed a rather brittle-like appearances. The surface bands formed with terminated ("frozen") tensile and compression load excursions were in fact surface ridges resembling the step-like surface features; such features are similar in shape to the surface ridges formed with repeatedly applied UL cycles in [18]. The surface ridges with varying textures, profiles and sizes appeared to be formed at different local surface planes positioned next to each other, along the same crack front during all applied test sequences.

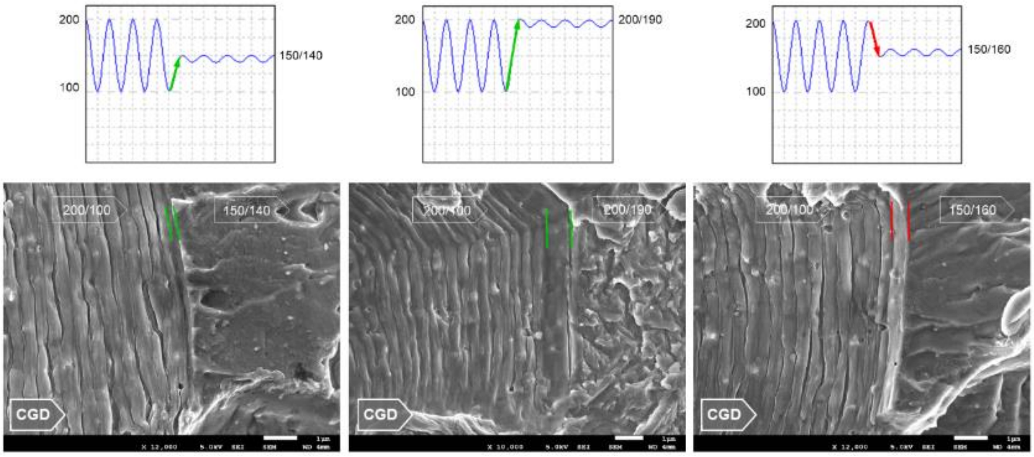

Figure 3: Typical appearance of fracture surfaces observed using frozen loading cycles.

The surface ridges (tip flanks) of relatively small sizes were formed on local surface planes when tensile load excursions of 100→150 MPa were applied. These ridges showed various profiles; ridges with more or less straight profiles, as well as ridges with slightly curved profiles, were locally formed on directly mating fracture surfaces (Figure 4-A). The profiles of newly formed ridges varied along the same crack front. Note that surface ridges of rather similar sizes and profiles were formed along the profile 2-2'; surface ridges of different sizes were measured along the profile 1-1'. The CA striations formed before the application of tensile excursion appeared to be formed on more or less straight plain with the exception of surface striations that were formed immediately prior the application of tensile excursion that cause the formation of surface ridge (crack flank). In this case, surface striations with visibly stretched profiles (out-of-plane) appeared to be formed on individual, and in some cases on directly mating, surfaces.

The detailed view, containing the measured mating profiles is shown in Figure 4-B. In this figure, measured surface profiles are plotted together to show the reconstruction of the crack tip as it is formed during the tested. Surface striations marked as 5-to-2 having the convex-shaped profiles are shown to on profile 3; regular striations are then followed by the striation with stretched and almost flat profile (marked as 1). On the directly mating side (profile 3'), striations marked as 5-to-2 are also shown to have convex-shaped profiles, although the profiles appeared to be less pronounced and somehow more complex when compared to those formed on profile 3. Striation marked as number 1 is then formed on the profile 3', having stretched-like convex-shaped profile. Surface profiles 3 and 3' are then connected via newly formed crack tip profile consisting of the surface flanks that are formed on each side of the crack.

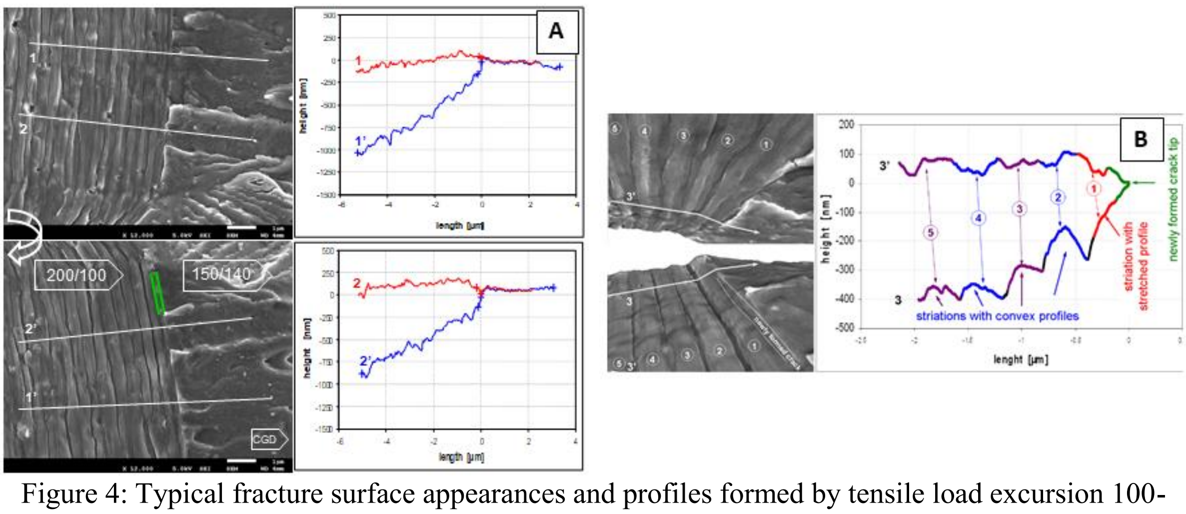

Figure 4: Typical fracture surface appearances and profiles formed by tensile load excursion 100-150MPa (in A); detail striation and crack tip flanks profiles in (B).

Striations formed on each profile not only show to have developed somehow different spatial profiles, but also the width (spacing) of striations appears to differ when corresponding striations on mating sides are compared to each other.
The micro-cracks, thought to be the initiation stages of newly formed surface fissures (troughs), were also locally observed at the bases of the newly formed crack tip flanks during application of tension load excursion 100→150 MPa. Formed micro-cracks showed to be discontinuous and position-dependent. Partially formed micro-cracks were observed at the bases of some crack tip flanks, disappearing abruptly along the same crack front. In most cases, micro-cracks appeared to be formed on one side of the crack, but they were not formed on the directly mating sides, except in limited cases Figure 6 shows the formation of micro-crack at the base of the newly formed tip flank (lower profile). Note that partially formed micro-crack is also depicted in this figure on the directly mating side (upper profile). Observed behaviour appeared to suggest that newly formed crack flanks are first formed during the application of tensile load and then micro-cracks are locally initiated at the bases of already formed flanks. The formation of micro-cracks (early fissures) can be considered to occur in the crack tip wake rather than at the very crack tip apex.

The crack tip flanks were observed to grow considerably in size during the application of further increased load excursions (100→200 MPa). Unexpectedly, a wide variety of surface ridges (and reconstructed crack tip profiles) were also observed (Figure 6). On many local fracture surface planes, surface ridges with more or less straight profiles and featureless textures were formed on both sides of the crack. The reconstruction of fracture surfaces revealed the formation of V-shaped crack tip profiles with mostly asymmetrically sized crack tip flanks on directly opposing sides of crack. CA striations with various textures and convex-shaped profiles were also formed on the same fracture surfaces; well visible surface fissures, separating individual striations formed on either both or on only one side of the crack were usually also observed.
When surface fissures were formed on the general fracture surfaces, they were usually also formed at the base of the newly formed surface ridge (tip flank). CA striations with out of plane profiles, positioned prior the surface ridge (tip flank) were also formed on studied fracture surfaces, as shown in Figure 6-D. The fracture surfaces with brittle-like (cleavage) appearances were formed immediately after the surface ridges; secondary cracks with wider and open-like appearances were commonly formed at the ridge-to-brittle surface transitions. In all observed cases, secondary cracks were formed on only one side of the crack. The position and asymmetry of formed secondary cracks suggests that two cracks were likely initiated during the load transition (tensile excursion to CA 200/190); secondary cracks were then stopped in growing shortly after their initiation, while the remaining crack will grow and eventually become the fracture surface with brittle-like appearance.

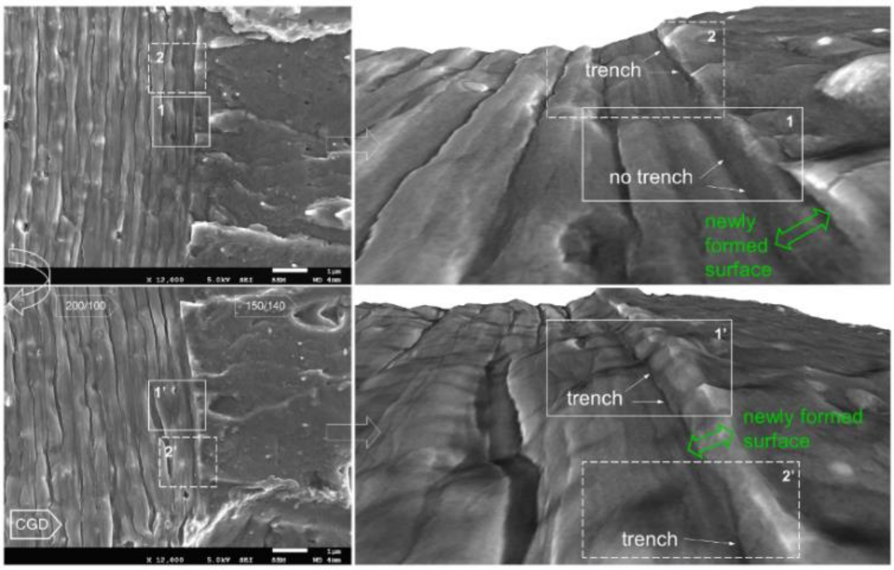

Figure 5: Surface fissures formed at the root of newly formed crack tip flanks, tensile load 100-150MPa.

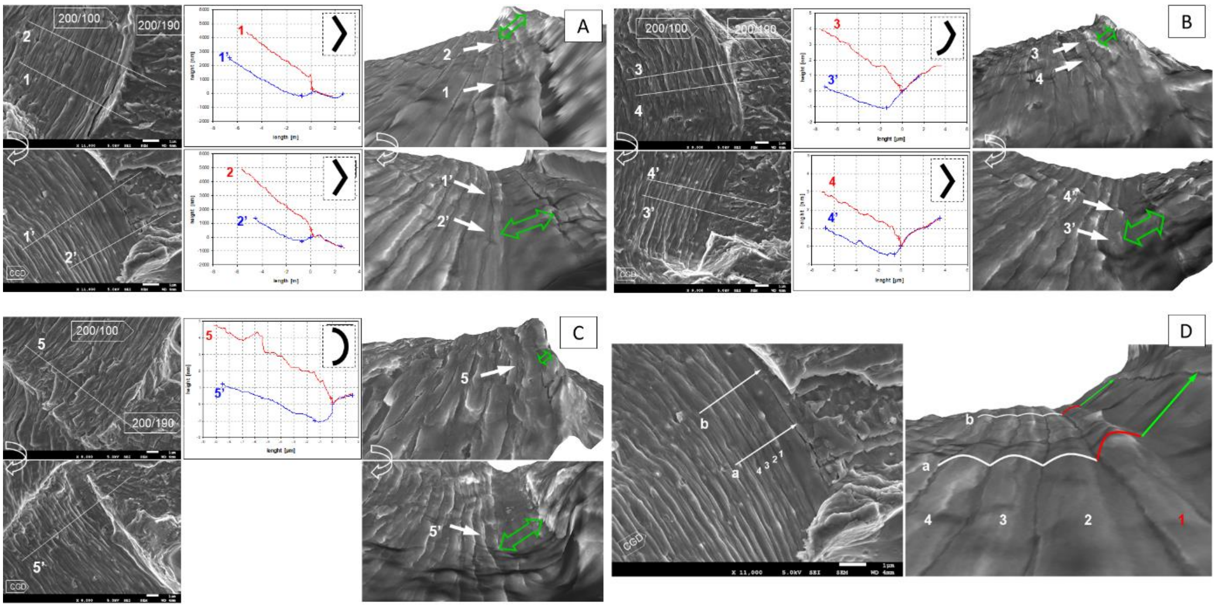

Figure 6: Typical fracture surface appearances and reconstructed profiles produced by tensile loading 100-200MPa; (A-C) various crack tip profiles produced; (D) stretching of striation in crack tip flank wake.

On other local surface areas, surface ridges with partially curved profiles, curved at the base and straight in the upper part of the profile, were also formed. The curved bases of the surface ridges were covered with layered, deformed-like, surface textures, but no micro-cracks or surface fissures were formed at the bases of curved surface ridges. Instead, continued transitions from previously formed CA striations into surface ridges formed by the load excursion were observed.

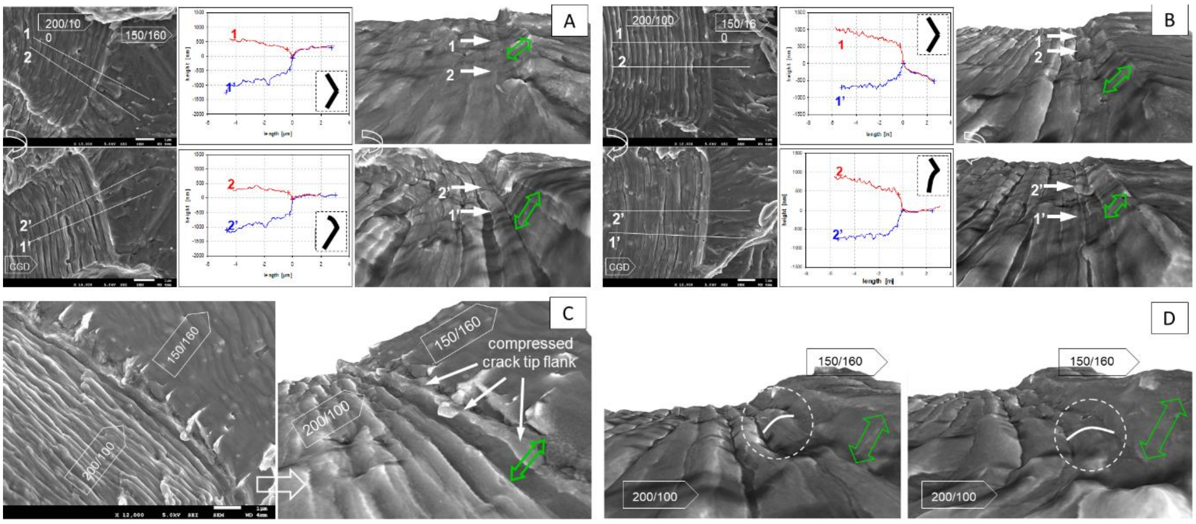

Figure 7: Appearance of fracture surfaces and reconstructed profiles, compressive load 200-150MPa. All measured tip profiles, obtained from fracture surfaces that were formed with tensile and compression load excursions were plotted and analysed. Collected data revealed good agreement between crack tip profile geometries and theoretical angles belonging to crystallographic planes (111) as noted by [6].

The CA striations themselves showed stretched, deformed, and rumpled or layered-like, surface textures, lacking the surface fissures (troughs). The surface ridges, rather straight and smaller in size, were formed at the directly mating sides of partially curved ridges; CA striations separated by narrow, but distinctly formed surface fissures, were formed on the same fracture surfaces. The surface fissures were formed at the very bases of surface ridges. The combination of mating profiles showed the formation of asymmetrically shaped crack tip profile, in appearance and in size. Occasionally, surface ridges with semi-circular (U-shaped) profiles were also formed on some local surface planes, particularly on those with larger tilting angles. In such cases, larger surface ridges with fully curved profiles were observed on one side of the crack; smaller ridges with more or less straight profiles were formed on directly mating sides. When combined, the crack tips with near semi-circular profiles were obtained (Figure 6-C). Observed differences in new crack tip formation appeared to suggest that considerably different, perhaps even contradicting, underlying mechanisms must be active in each case.

When compression load excursions were applied (200→150 MPa), surface ridges of considerable sizes with relatively straight, partially curved and band (buckled) profiles were mostly formed on local surface plans (Figure 8). Occasionally, surface ridges with partially compressed-like or plastically deformed profiles, were also observed as shown in Figure 7. CA striations with various textures, but with ductile, convex-shaped profiles were formed. Striations formed immediately before the surface ridges showed various levels of stretching; striations with slightly stretched, compressed and fully convex-shaped profiles were observed locally, as shown in Figure 7-D.
Observed behaviour suggests that only limited and localized deformation of the newly formed crack tip flanks (surface ridges) occurred during the application of compression load excursion (200→150 MPa). On the contrary, previously formed and stretched CA striations seem to be affected the most. Further increased level of compressive stress will have to be applied on to specimen to close the newly formed crack tip completely, creating striations on both mating sides of the crack.

The agreement between measured and theoretical data suggests that the sharp crack tip flanks likely grow along the crystallographic planes (111) with general fracture surfaces being formed along either (100) or (110) crystallographic planes, as shown in Figure 8. Ideal crystallographic profiles are tilted in the graphs to match the orientations of reconstructed crack tip profiles.

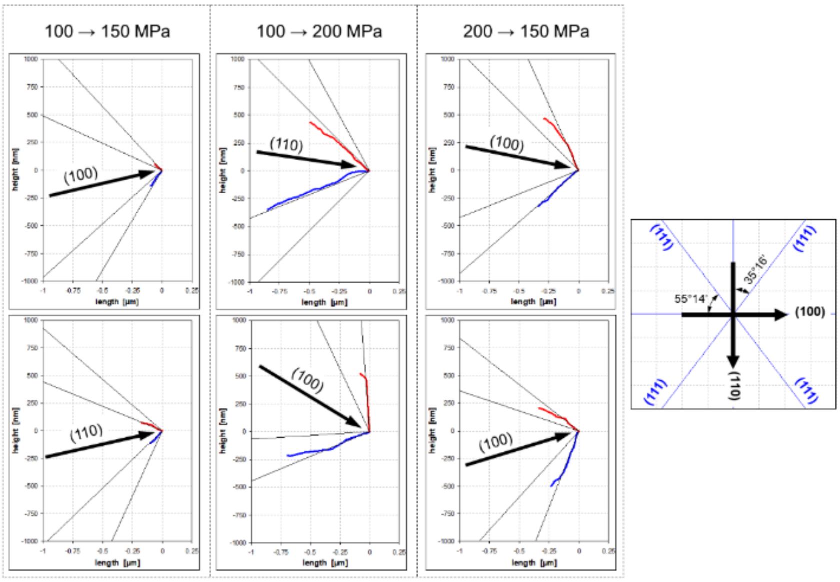

Figure 8: Crack tip reconstructions and corresponding ideal crystallographic planes [6].

DISCUSSION

Intrinsic crack tip behaviour

One of the most striking observations of this study was that sharp, V-shaped, crack tip profiles could be formed alongside crack tip profiles with more round, near semi-circular, U-shape.
In all known models, each of these profiles is commonly associated with different, and fundamentally opposing, deformation mechanisms. In most models concerning the formation of sharp V-shaped crack

tip profiles [3][6],[13], only the very crack tip apex is considered to be actively accommodating the generation and movement of dislocations along the [+,+] & [+,-] directions. The dislocations along the crack tip flanks are considered immobile (terminated) as shown in Figure **Error! Reference source not found.**-A. On the contrary, the formation of semi-circular U-shaped profiles assume occurring homogeneous and continuous plastic deformation [9],[11],[17] that is accommodated via emission and movement of dislocations that are active around the entire crack tip, as depicted in **Error! Reference source not found.** Figure -B . Considering the exclusive nature of plastic deformation (directionality and scale) in both cases, formation at the same time of sharp V-shaped and blunted semi-circular U-shaped crack tip profiles are not expected to occur.

In [10] the crack tip profiles, and consequently the shapes of surface striations, depend upon the orientation of the local fracture planes and on the available slip system with respect to the tensile and shear stresses generated at the very tip of growing cracks. If the crack is growing in the local planes with orthogonal orientation with respect to the far field load direction, the slip systems of maximum resolved shear stress will be symmetrically disposed around the crack tip and equal amounts of shear slip will occur on both sides of the crack tip. This configuration will result in the formation of symmetrically shaped crack tip profile during application of the tensile load excursion. If cracks are growing on tilted local fracture planes, the slip systems of maximum resolved shear stress would not be symmetrically distributed around crack tip. The preferential direction of deformation would be expected along the directions of [+; +] and [-; -], resulting in the formation of a crack tip with asymmetrically stretched and deformed crack tip flanks. The crack profiles and local fracture surface planes observed in this study followed the similar pattern. The reconstructed profiles are graphically depicted in **Error! Reference source not found.**Figure –C, D and E. From this argumentation, it appears that it is possible for the crack to grow via asymmetrically deformed crack tip flanks, depending on the local crack plane orientation and the availability of shear slip systems.

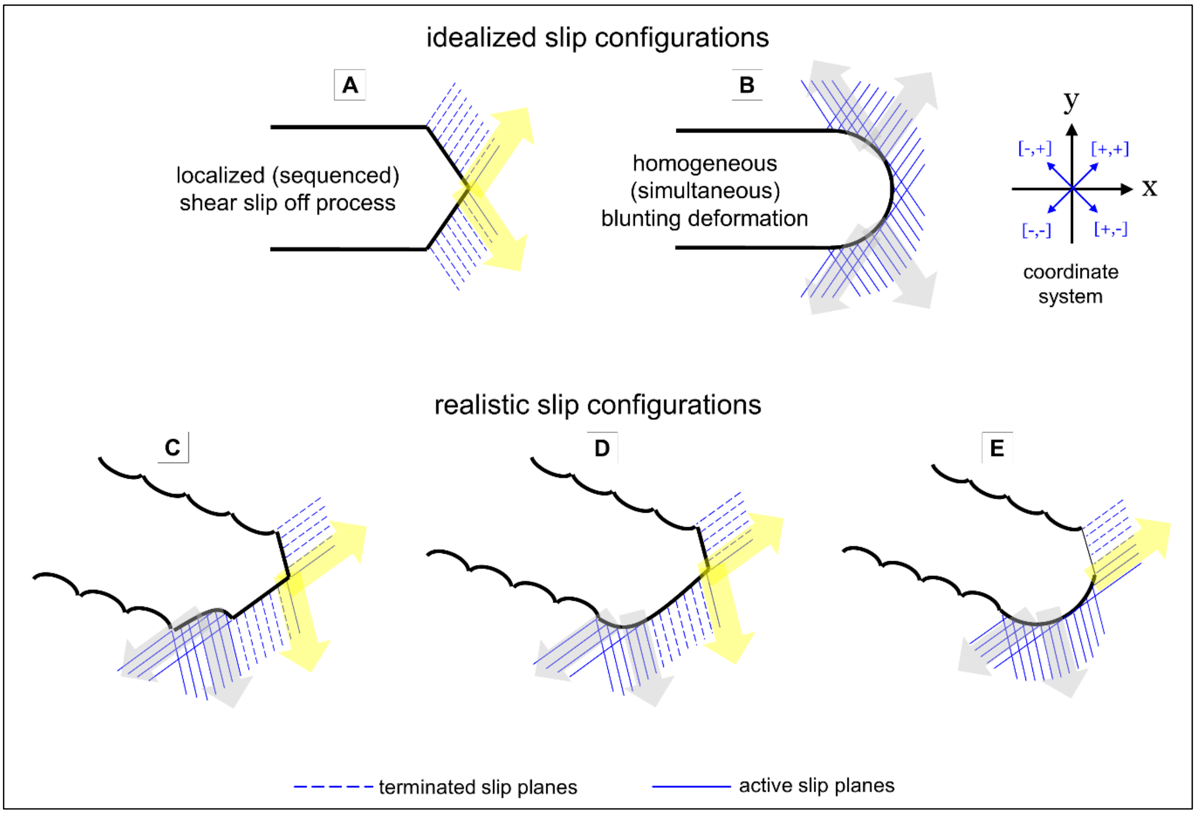

Figure 9: Crack tip profiles with assumed dislocation behaviour; (A) localized shear slip process in sharp V-shaped crack tips [3]; (B) homogeneous blunting in U-shaped crack tips [9]; (C-E) combined localized shear and homogeneous blunting process.

Also in [10], the closure of the asymmetrically shaped crack tip during the application of compression load excursion would occur behind the crack tip rather than directly at the crack tip apex. This way, the fissures would form on either sides of the crack and the surface striations with interlocking striations with convex – concave profile pairs or the surface striation with interlocking intermediate profiles (mixed type) would be formed on the directly mating fracture surfaces. However, no interlocking (convex-concave) were observed in this work, but instead mirrored (convex-convex) ductile surface striations of type A and striations of mirrored mixed striations. To form such striations, it is considered that crack tip flanks are formed during the application of tensile load excursion, plastically deformed during the application of compressive load excursion and cyclically deformed (stretched - collapsed) in the wake of new active crack tip. This process is discussed in more detail the subsequent paragraph.

Extrinsic crack wake behaviour

The mechanism by which the fracture surface features could be repeatedly deformed in the crack wake by cyclically applied loads and which contributes to shaping of surface striations, has not been well-considered in published literature. As such, the introduction of this multi-cycle deformation process constitutes the most novel mechanistic explanation contributing to the field of fatigue crack growth micro mechanics. Interestingly, wider crack tip opening in and at the vicinity of the crack tip has been noted before [19],[20], especially in work focusing on the crack tip opening displacement (CTOD) and its correlation with crack growth driving parameters.

Kuo & Liu [8] and Liu [1] build their crack growth model on the assumptions that crack tip will be formed along the particular shear bands that will be concentrated around the crack tip and that the deformation would also be carried out along the same bands even when far behind the crack tip apex. In their work, these authors argued that deformation that takes place results in wider crack tip blunting, but that this process does not contribute to the overall crack growth or formation of surface striations. Therefore, they postulate that zipping and unzipping, as they labelled this deformation process, which occurs near the very crack tip apex, should be only taken into the consideration for the crack tip growth during the application of the tensile and compression load excursions. The current work, however, seems to disagree with this notion.

Another interesting work was, that may be related to the multi-cycle deformation occurring in the crack wake was reported by Wanhill [12]. In this work, formation of dislocation substructures that were associated with the surface striations was investigated. Wanhill reported that bands of denser and less dense dislocation structures were formed in wet air under the surface striations. The explanation of this phenomena was provided, in which the denser dislocation bands were formed ahead crack tip flanks during the crack opening (tensile load); the dislocation substructure is thought to reconfigure (dislocation shake down process) during the crack tip flanks closure (compression load) resulting in formation of less dense dislocation band under formed striations. The reconfiguration of the dislocations will reduce the density of dislocation under the leading side of surface striations (near crack tip).
Similar formation of dislocation bands under the surface striations were reported by Nix & Flowers [10], but they proposed a different mechanism of their formation. They assumed that the crack tip will initially start to propagate via brittle tensile decohesion process, a process that will be associated with little plastic deformation. Only during the further increase in tensile load, more plastic deformation occurs at the crack tip, which will be accompanied with the production and movement of considerable amount of dislocations. In their model, dense dislocation band form under the leading side of the striation, a band containing little or no dislocations will be formed under the trailing side. Since the trailing side is considered to be formed by brittle decohesion process, the surface reveals featureless appearance; in contrast, considerable plastic deformation would lead to the formation of surface with plastically deformed appearance.

Gained understanding governing the formation of plastic striations with convex profiles (type A) via cyclic plastic deformation of crack tip flanks is graphically depicted in Figure 10**Error! Reference source not found.**. In this figure, the formation of crack tip flanks C and D, are shown in the sequence: (1) the formation of new crack tip flank, (2) partial plastic compressive deformation of the crack tip apex, (3) plastic stretching in the crack wake and (3) the final compression in to the final shape. The

stretching of the striations in step 3 can take two distantly different forms. In the case of the model C, the stretching out of crack plane is considered; a process that will increase the height of the striation profile. In the case of model D, the stretching along the crack plane is considered; a process that would decrease the height but may increase the width of the striation. The formation of dislocations and their movement along the set of crystallographic planes (111) is considered in step (1), the reverse movement of dislocations along the same plane is considered in step (2). The initiation of new dislocations and their movement on new crystallographic planes are considered during the material stretching in step (3) and finally, the reverse movement of dislocations activated in previous step is considered in step (4).
As illustrated in Figure 10**Error! Reference source not found.**, significantly different amount of plastic deformation is to be expected at the leading and at trailing sides of the surface striation at the end of step (4), particularly in the model C. The model C describes the creation process for formation of ductile striations with fully convex profile (Type A), being partially covered with rippled surface. The difference in plastic deformation at the leading and at the trailing side will be less pronounced as the striation have to change its profile considerable during the cyclic loading. However, it would be reasonable to assume that denser dislocation structure will also be formed underneath the leading side of striation because considerable larger amount of plastic deformation should occur on this side. This model attempts to describe the formation of mixed mode striation, which is essentially the deformed striation of Type A.

The formation of dislocation substructures of different densities during the load cycling, as experimentally observed and reported by Wanhill [12] and Nix & Flowers [10], may also be responsible for the formation of surface fissures. As already discussed above, the dislocation substructure will be already formed under the partially compressed striations (the end of stage 2), while new dislocation will be generated into the virgin material when new crack flank is being formed. One could therefore speculate that fissures would initiate at this interface (cyclic dislocation band versus newly formed dislocations), in sort of shear or delamination type of failure, and they would further grow in size in the wake of the crack tip during the subsequently applied load cycles. Secondary cracks will grow along the favourable crystallographic planes during applied load cycles, exposing the surfaces with rippled like appearances. This is the process proposed for the formation of secondary cracks frequently observed on the fracture surfaces formed by CA sequences, shown in **Error! Reference source not found.Error! Reference source not found.**.

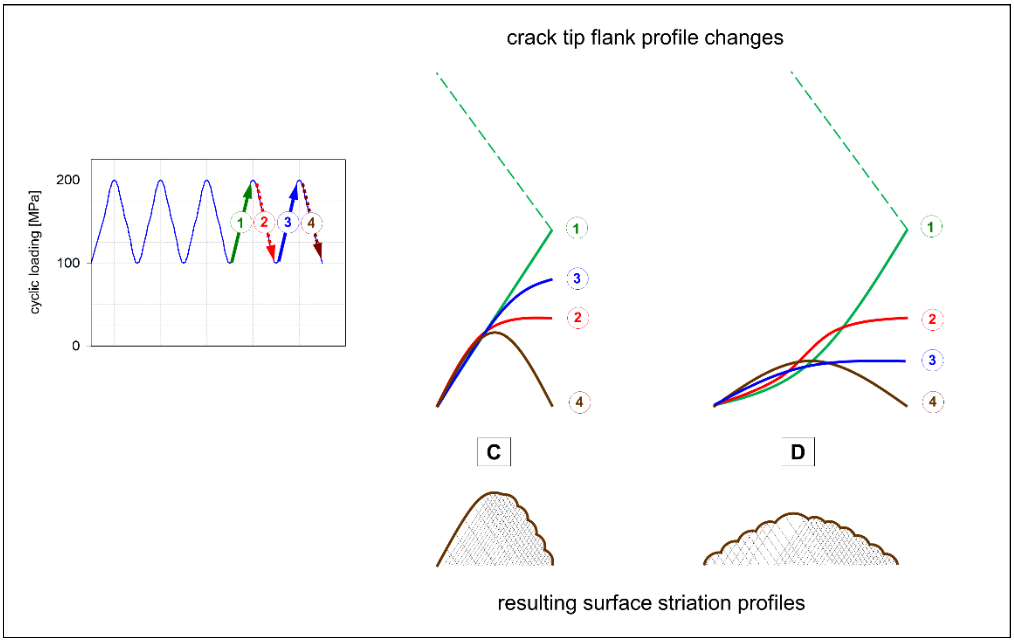

Figure 10: Schematic illustration of crack tip flank formation during applied cyclic loads 1-2; partial tip flank deformation during consequently applied load cycles (3-4) in crack wake. Resulting surface striation profiles with underlying plastic deformation patterns also included.

PROPOSED MECHANISTIC MODEL

Combining information gathered from the fractographic study characterizing the fracture features produced by CA loading, and from the study of the crack tip evolution during the tensile and compression loading, a comprehensive mechanistic model is proposed. The model shown in Figure 11 describes graphically how cracks can grow utilizing three distinct profiles, marked as sub-model A, B and C, respectively.

Sub-model A:
The crack tip is assumed to be a profile with a sharp, partially closed profile at the minimum load (100MPa). During the application of small load excursion (100-150MPa), new crack tip flanks of uneven sizes, maintaining V-shaped profile at the crack tip, are initiated on both sides of the crack, maintaining the V-shaped profile. The previously formed striation positioned at the lower side is severely plastically deformed (stretching) during this stage, while a striation on the upper side of crack also deformed, but to lesser extent, when compared to the striation at the lower side. Formation of surface fissure is initiated at the base of lower crack tip flank. During further increase of load (150-200 MPa), the initiated crack tip flanks grow in size; with a larger flank at the lower side, while the crack tip maintains the V-shaped profile. Fissures formed in the crack tip wake may grow slightly during this loading stage, but no further plastic deformation of striations in crack wake occurs. During the partial compression (200-150 MPa), only the apex of the crack tip is compressed and deformed. The most notable change occurs at previously stretched striations positioned in the crack wake: striations on lower side compress to near final profile, while striations positioned at upper side also compress, but to lesser extent. During the final compression (150-100MPa), the crack tip apex is further compressed, where striations formed in the crack wake assume their final shape. Ductile striations with convex profile (type A) are formed at the lower side; striations with less regular, but overall convex profiles (deformed Type A), form at the upper side of the crack.

Sub-model B:
The crack tip is also assumed to be the sharp notch in sub-model B at the minimum load (100 MPa). During application of small tensile load (100-150 MPa), the crack is initiated maintaining the V-shaped profile at its apex. The base of lower side of crack tip maintains continues and curved profile that is stretched along the local plane direction, no surface fissure is formed on this side of crack. The striation that was formed during the previous load cycle, having S-shaped profile, is also stretched along the crack plane, a process that is decreasing the overall height of this striation. The crack tip flank positioned at the upper side of crack has an entirely straight profile, where a surface fissure forms at the base of this flank. During further increase in load (150-200 MPa), the crack tip increases in size, while the tip flanks maintain their profiles: the upper flank maintains its straight profile, while the lower profile only remains straight close to the crack tip apex and curved profile near its base. Surface fissures formed at the base of the upper flank and further in the crack wake can grow in size. During the final compression (150-100 MPa), the crack tip flanks are further closing at the tip apex, with the lower flank experiencing more plastic deformation. Previously formed striations are compressed into their final shapes, characteristic for their local planes. Surface fissures are closing.

Sub-model C:
The sub-model C is in many aspects identical with sub-model B, with the exception of excessive plastic deformation at the larger portion of the lower crack tip flank during the applied tensile loading. This deformation results in formation of crack tip profiles with round profile. Striations formed on this fracture plane showed to be of the mixed type (deformed Type A) mostly due to the more complex deformation process occurring on curved profile during the crack tip closure.

The presented model with its three sub-models, explains the crack growth behaviour at medium depths (3-4 mm). One could ask how a crack grows at shorter and at larger crack depths? It was observed fractographically, that general fracture surface topography evolves along different crack depth. Fracture surfaces with brittle like appearance were observed near the starter notch; fracture surfaces consisting of local planes with near orthogonal orientations or with small deviations from this orientation were formed in crack depths of 1-2 mm. The local fracture surface tilting appeared to increase along the increasing crack depth, especially at crack depths of 5 mm and deeper. The onset of static overload was observed at further crack depths. It was also observed that striations depicted in the sub-model A appeared to be formed on planes with slightly tilted orientations, behaviour depicted in sub-model C is predominantly applicable to striations formed on significantly tilted fracture planes. One could therefore speculate that cracks begin to grow at short crack depths according to sub-model A. Plastic striations with convex-shaped profiles form on directly mating fracture surfaces, while surface fissures separating individual striations could form on one side only or at both mating fracture sides. Crack will then mostly grow according to sub-models A, B and C, respectively, at medium crack depths (3-4 mm) as directly observed experimentally in this study. At greater crack depths, crack growth according to models B and C could be expected. This will result in creation of mating fracture surfaces having considerably different appearances; surface striations with distorted and extensive deformed appearances will be formed. Deep surface surfaces and large secondary cracks will also be observed on such fracture surfaces. Such expectations agree with results obtained in fractographic studies.

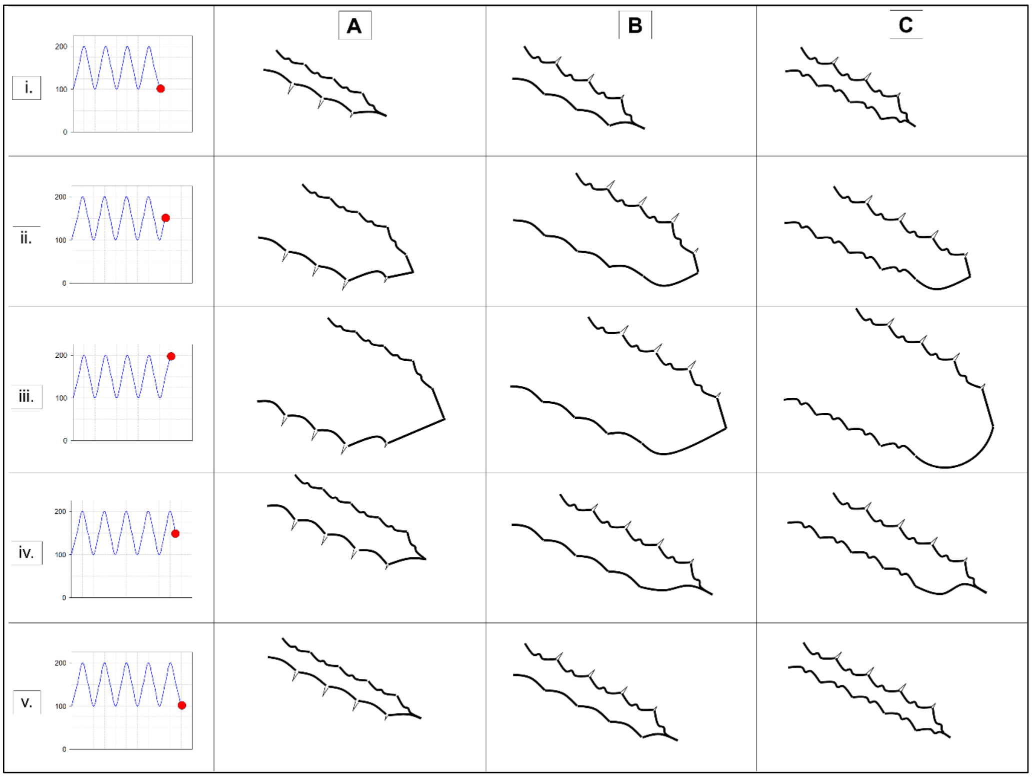

Figure 11. Proposed mechanistic model for crack advancement during applied load cycle, maintaining (A) sharp V-shaped profile; (B) partially sharp V-shaped/partially circular crack tip profile and (C) near circular crack tip profiles.

CONCLUSION

Traditional fracture mechanics assumes that crack growth in Paris regime is the result of a competition between intrinsic growth mechanisms, occurring at and ahead of the crack tip, and extrinsic retardation mechanisms, taking place in the crack wake. Proposed mechanistic models developed to explain the formation of fracture surface features operate with the assumptions that (i.) the intrinsic mechanisms are entirely responsible for the formation of surface striations left on the fracture surface; and (ii.) the crack tip of specific profile is formed in response to cyclic loading. It is usually assumed that the extrinsic retardation mechanisms will affect the dynamics of the crack growth, but will not the appearance of the fracture surface features left in the crack wake, and that only limited and isolated deformation patterns may be formed and detectable.

It could be concluded that fatigue cracks grows assuming various tip profiles, and associated plastic deformation characteristics, along increasing crack depths and SIFs. In particular:

- at shorter crack depths (<2 mm), the crack tip grows maintaining predominantly symmetric, V-shaped profile;
- at slightly increased crack depths (2-4 mm), the crack tip grows maintaining various, distinctly different profiles: asymmetric, V-shaped profile; asymmetric, partially plastically distorted V-shaped profile; profile with apparent blunt, asymmetric U-shaped profile.
- at further crack depths (>5 mm), the crack tip is assumed to grow maintaining predominantly asymmetric, blunt, U-shaped profile.

The formation of asymmetrically shaped crack tip profiles, be it V or U-shaped, is associated with the tilting of the local fracture planes with respect to the far field load. The evidence also supports the idea that crack tips maintaining sharp, V-shaped, be it symmetric or asymmetric, are likely growing along the crystallographic planes (100) or (110), forming new crack tip flanks along crystallographic planes (111). The character of formed cracks with blunt profiles, with respect to the crystallographic orientation of material, is unknown.

It can be also concluded that the formation of the fracture surface features is the product of the synergy between intrinsic and extrinsic mechanisms. The cyclic deformation of surface striations positioned in the wake of active crack tip was observed experimentally; this process has direct effect on the formation of striations with convex profiles and characteristic rippled textures. The same process has also direct effect on the growth of surface fissures, surface discontinuities that are cyclically grown in the crack wake into the secondary cracks, features commonly observed on fatigue fracture surfaces.

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