MODELS OF FATIGUE CRACK INITIATION

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Experimental evidence concerning the surface relief evolution and crack initiation in crystalline materials is presented. The models describing the mechanisms of fatigue crack initiation are reviewed. Recent models based on the cyclic slip localisation and taking into account the dislocation structure of persistent slip bands are described and confronted with experimental observations.

1. Introduction

The study of the mechanisms of fatigue damage in structural materials proved to be indispensable for the optimisation and improvement of the fatigue resistance of materials and for the refinement of the fatigue life prediction procedures of components and structures. The intense study of the damage evolution in crystalline materials subjected to cyclic loading has several distinct characteristic stages. Figure 1 shows schematically the main stages and substages of the fatigue damage evolution in fatigue of structural materials. From the engineering point of view, the macrocrack initiation represents the fatigue process up to the appearance of a crack visible by a naked eye or by an eye instrumented by magnifying glass, i.e. having a length of several tenths of a millimetre. This stage comprises the true initiation or nucleation of a microcrack and also short crack growth. Here only the first stage, i. e. the microcrack initiation will be studied.

From the analysis of the numerous examples of service fatigue fractures of components and structures as well from the study of laboratory specimens subjected to different loading and environmental conditions two basic cases of crack initiation can be found. The crack is initiated either in a rather homogeneous stress field, usually from the surface, or in a site of stress concentration, caused by some macrodefect as inclusion or a discontinuity. The process of crack nucleation is, however, very similar in both cases if local stress and strain fields are considered. The crack growth, on the other hand, is strongly influenced by the stress gradient. The subsurface initiation is relatively rare and is observed in case of anisotropic materials, materials with defects or in materials covered by a hard surface layer.

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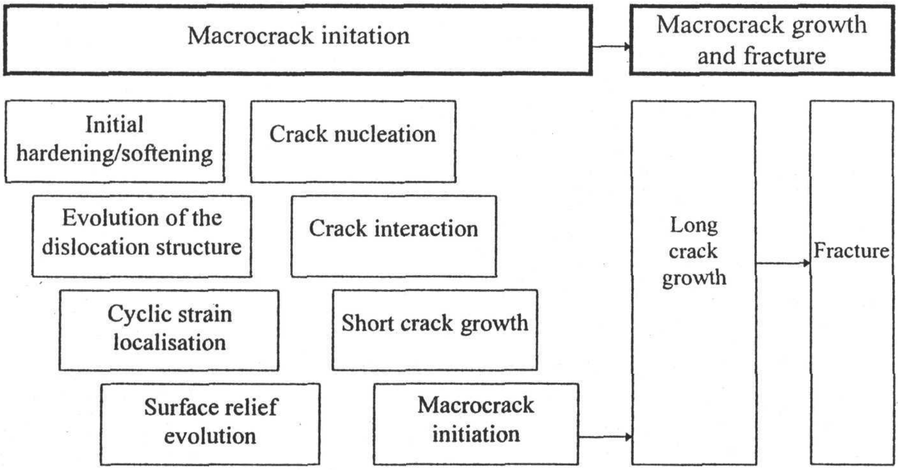

Fig. 1. Damage stages in fatigue of materials.

The subject of the present contribution is to review contemporary models describing the mechanisms of the nucleation of fatigue microcracks starting from a free surface.

2. Historical development

The fatigue crack initiation has been studied shortly after the phenomenon of fatigue of materials has been identified. Ewing and Humfrey [1] at the onset of this century used optical microscope to study the surface relief changes of the fatigued polycrystalline Swedish iron. Already these first observations revealed the inhomogeneous distribution of the surface damage and its localisation in the bands.

Further important progress in the understanding of the mechanisms of the fatigue damage could not happen before the discovery of dislocations and their role in plastic deformation and in cyclic plastic straining of crystalline materials. The early models tried to explain the interesting experimental findings of Forsyth [2] who observed extrusion formation on the surface of fatigued light metal alloys.

Another impulse in the research concerning the fatigue crack nucleation was the use of high-resolution techniques as transmission electron microscopy, scanning electron microscopy, and, recently, atomic force microscopy. They were applied to the study of the internal dislocation structures and to the study of the surface changes induced by fatigue. The experimental investigation of the crack initiation in single crystals of a known orientation allowed to obtain the information on the relation between the internal structure and the surface relief evolution. The proposed models have to take into consideration the numerous experimental data and to explain the observed sequence of events.

3. Models based on individual dislocation mechanisms

The early models of fatigue crack initiation have been summarised in a number of books or review articles [3–6]. Cottrell and Hull [7] consider two dislocation sources in different planes corresponding to two highly stressed slip systems close to the surface. Alternate activation of these two sources can produce an extrusion-intrusion pair. Wood [8] proposed the card slip to create the extrusion-intrusion pair. Mott [9] considered the irreversible motion of a screw dislocations to extrude locally material from the inner part to the surface. Kennedy [3] modified the model and introduced simultaneous motion of edge dislocation and formation of Lommer-Cottrell locks which result in irreversible motion of the screws with the cross slip. Another modification of the original Mott's mechanisms was proposed by McEvily and Machlin [10]. The formation of extrusions by the interaction of the edge and screw dislocations and by formation of unit dislocation dipoles by a non-conservative motion of the jogs on screw dislocations, is proposed by Thompson [11] and Watts [12].

All these models were proposed before the relevant information concerning the relief and internal dislocation structure in fatigued materials was assessed. They are based on specific dislocation configuration and their rather artificial motion during the loading cycle. It is difficult to reconcile them with the actual dislocation arrangements and real surface relief formation.

4. Models based on interaction of dislocations in localised slip bands

4.1 Experimental observations

Experimental studies of the internal structure of the localised slip bands (later called persistent slip bands – PSBs) and of the surface relief evolution in single- and in polycrystalline materials were the impetus for the formation of the advanced models of fatigue crack initiations.

The relevant information has been collected on copper single crystals [13–16]. These studies promoted creation of a spatial model of dislocation structure of the PSB. The relief produced on the originally polished surface of a copper single crystal fatigued with constant plastic strain amplitude in the domain of saturation of the shear stress amplitude is shown in Fig. 2 [17]. The surface of the single crystal between the edges of the extensometer is covered by persistent slip macrobands and by individual PSBs. The slip bands follow the intersection of the primary slip plane with the surface and are separated by areas of a smooth surface. In Fig. 2a both macroband and an individual PSB is shown. The macrobands consist of densely spaced individual bands but protrude above the original surface. This protrusion

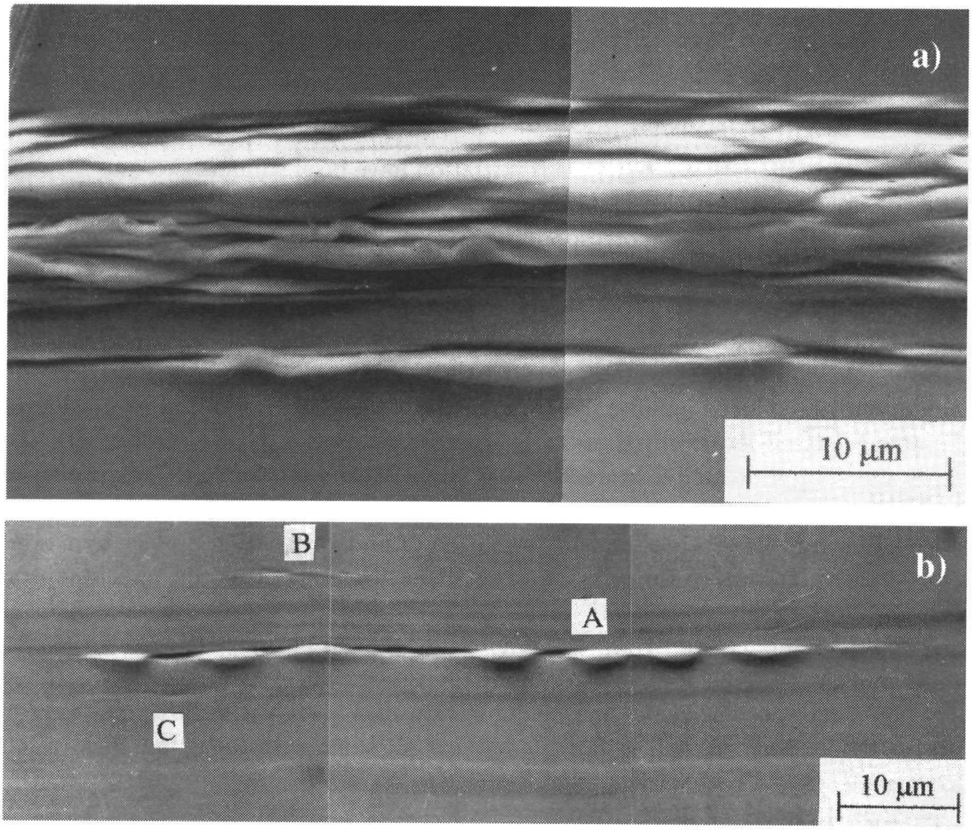

Fig. 2. Surface of fatigued copper single crystal (SEM), a) macroband and individual PSB, b) short PSB (A) and two embryonic PSBs (B and C).

has been studied more thoroughly [18] around the specimen circumference. The short individual PSBs (A) and two nuclei of PSBs (B and C) in Fig. 2b suggest that PSBs are nucleated at the surface and in the early stage of development produce alternating depressions and elevations of the crystal surface. Although direct evidence does not exist, a semicircular form of the PSB nuclei is supposed. During the fatigue life the depressions deepen and elevations grow until they become intrusions and extrusions, respectively. The well-developed PSBs contain nucleated cracks. The cracks are often hidden below the tongue like extrusions. In some cases (Fig. 2a), the crack cuts the tongue-like extrusion which gives suggestion concerning the mechanisms of early shallow crack nucleation.

The distance s between two neighbouring extrusions or intrusions at the early stage of PSB development was related to the distance d between neighbouring lamellae in the ladder structure [17]

$$s = d/\cos\alpha, \tag{1}$$

where α is the angle between the Burgers vector and the tangent to the line in which the primary slip plane intersects the surface.

Similar experimental observations were made on polycrystalline materials. Fig. 3 shows high magnification SEM micrograph of the surface grain of 316L stainless steel cycled to the domain of saturation of the stress. In Fig. 3a the primary electron beam was perpendicular to the surface, in Fig. 3b the specimen was inclined approximately 35° and the primary electron beam was parallel to the primary slip plane. The extrusion in the centre of the band is inclined to the surface and follows the active primary plane. It is accompanied by two small parallel intrusions at the interface with the matrix.

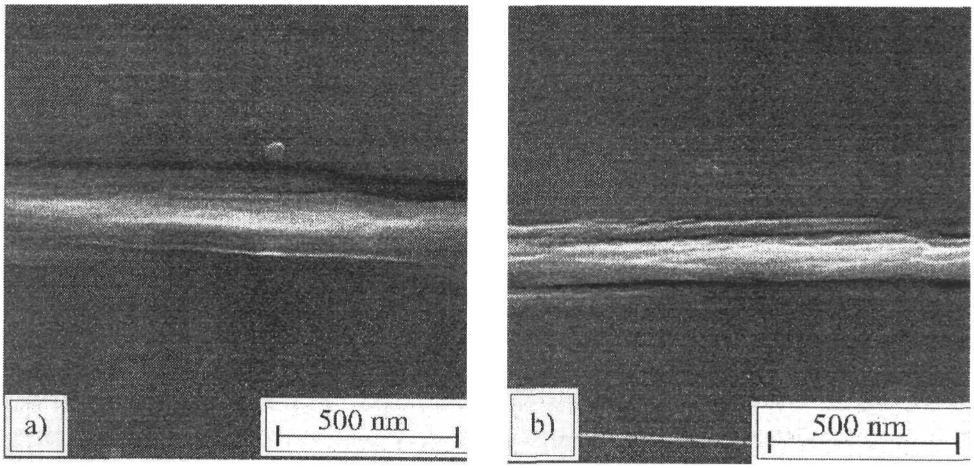

Fig. 3. Surface relief in a grain of fatigued 316L steel (SEM), a) primary beam perpendicular to the surface, b) primary beam parallel to the slip plane.

Neumann and Tönennsen [20] in polycrystalline copper and Heinz and Neumann [21] in polycrystalline austenitic steel made another important observation. They observed cyclic slip localisation accompanied by extrusion and intrusion formation both in PSBs and in twin boundaries. However, the fatigue cracks initiated preferably in every second twin boundary. The local stress concentration due to elastic anisotropy was used to explain the promotion of the cyclic slip in a suitably oriented twin boundary.

4.2 Models of surface relief formation

The ladder-like dislocation structure of an individual PSB in the copper single crystal revealed by transmission electron microscopy led Antonopulos et al. [22] and Essmann et al. [24] to propose a model of a PSB in terms of dislocation dipoles. The formation of dipoles leads to the creation of extrusions or intrusions when they egress on the surface. These considerations resulted in a well known Essmann, Gössele, and Mughrabi model (EGM model) [24] in which the principal role is played by point defects that are produced during cyclic plastic deformation in the PSB. The point defect concentrations produced in cyclic straining were confirmed by electrical resistivity measurements [25, 26]. In the original model the interface dislocations are produced at the boundary between the PSB and the matrix. Since these interface dislocations are pushed to the specimen surface, the PSB lamella becomes elongated in the direction of the active slip vector. If $c_{\nu\,\mathrm{sat}}$ is the saturated vacancy concentration in the PSB, the height h of the static extrusion is proportional to saturated vacancy concentration $c_{\nu\,\mathrm{sat}}$ and to the depth D of a PSB in the direction of the primary Burgers vector

$$h = c_{\nu\,\mathrm{sat}} D. \tag{2}$$

The profile of the static extrusion is roughened later in the fatigue life by random slip. Random slip was treated in detail by Differt et al. [27] using statistical theory of the slip irreversibility in PSBs. The surface roughness, defined as a difference of the highest and lowest point in the PSB due to random slip, is proportional to the square root of the number of loading cycles. The predictions of the random slip model are not in agreement with experimental observations.

Similar models, based on the accumulation of vacancy and interstitial dipoles or dislocation pile-ups, were proposed by Antonopulos et al. [22], Tanaka and Mura [28] and Cheng and Laird [29]. The predictions of these models are only in partial agreement with experimental observations.

The analysis of the geometry of extrusions and intrusions, the relation between the internal dislocation structure and the surface relief, the interaction of the dislocations during cyclic straining, and the formation of point defects in PSB and their migration to sinks led Polák [30] to propose a new model of surface relief formation and microcrack nucleation. Individual PSB undergoing high cyclic plastic deformation (about 1%) in a quasi-elastic matrix is considered. Schematic structure of PSB and dislocation interactions within PSB in a single crystal or in a grain of a polycrystal is shown in Fig. 4. A slab of PSB consists of thin parallel dipolar walls separated by thick dislocation-poor channels. The surrounding matrix structure consists of loop patches or veins separated by irregular channels.

High plastic strain amplitude within the PSB is accommodated by the bowing of dislocation segments from the walls and their extension until edge segments reach the neighbouring wall. Screw segments carry most of the strain until they are annihilated by cross-slip with opposite screw dislocation moving on the parallel plane [30]. The point defects are formed either by the interaction of two edge dislocations moving on the neighbouring planes (Fig. 4) or by dragging jogs on screw dislocations [31]. Since activation energy of vacancy formation is much smaller than the activation energy of the formation of an interstitial, mostly vacancy type defects are produced in cyclic straining. The rate of vacancy production in room-temperature cyclic straining of copper with plastic strain amplitude of 1% was evaluated from resistivity measurements as high as 2.5×10^{-6} per cycle [26].

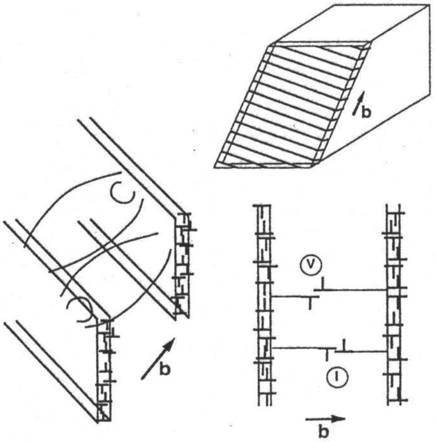

Fig. 4. Schematic representation of a PSB and the interactions of edge dislocations.

If vacancies or vacancy-type defects (e.g. di-vacancies) are mobile at ambient temperature, they will migrate to sinks. The excess vacancy concentration will thus depend on the sink density. Edge dislocations or edge dipoles represent a perfect sink for vacancies. Since their density is much higher in the walls than in the channels, inhomogeneous excess vacancy concentration arises. Fig. 5 shows the three-dimensional picture of a PSB intersecting a free surface and a section through a PSB in yz plane. The profiles of the excess vacancy concentration in two directions are shown, too. The one along the PSB results in periodic variation of the vacancy concentration that reaches minimum at the walls and maximum in the middle of the channels. Thus vacancies within the PSB will migrate from the channels to the walls.

In a section cut in the centre of the channel normal to the band direction the maximum vacancy concentration is reached in the centre of the band. It decreases in direction of the matrix since no point defects are generated in the matrix but matrix structure is a perfect sink for migrating vacancies. In a quasi-steady situation, the vacancy gradient results in a systematic flux of vacancies according to Fick's law. The arrows in Fig. 5b in z-direction show the vacancy flux out of the PSB to the matrix.

Let us consider the consequences of the steady flux of vacancies within the PSB (Fig. 5). The steady flow of vacancies in one direction results in transport of atoms in the opposite direction. The mass will be thus accumulated in the channels and decline in the walls. The direction of the transport of the mass in the y-direction

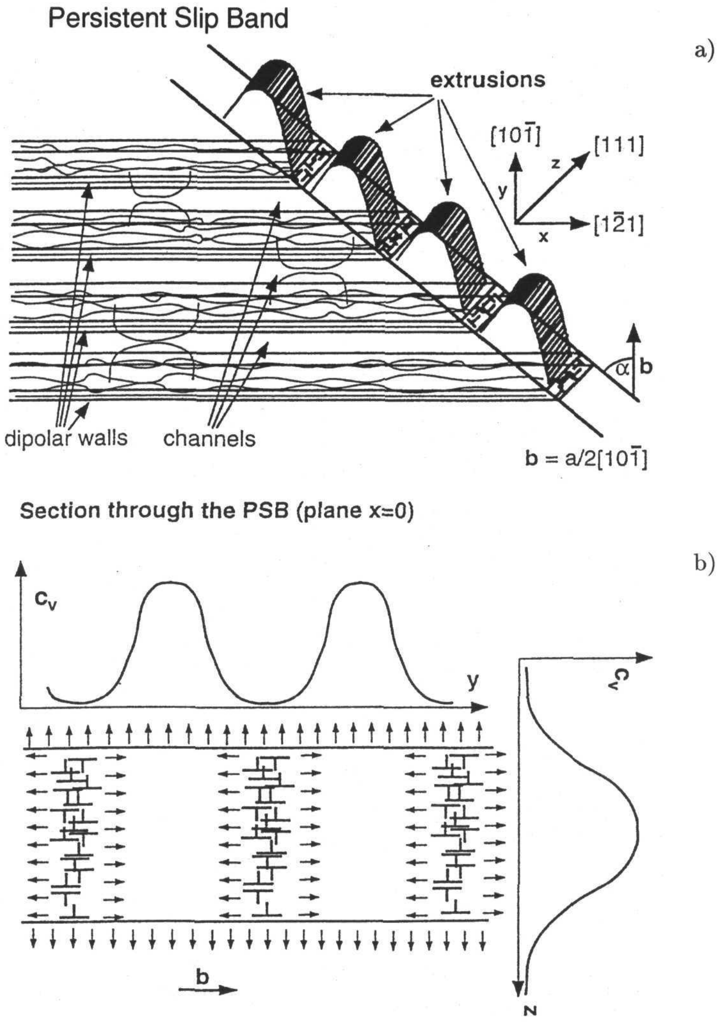

Fig. 5. The three-dimensional schematic picture of a PSB intersecting free surface (a) and a section through a PSB in yz plane (b).

within the PSB is indicated in Fig. 5b by arrows. The accrual and the loss of the mass in y-direction compensate mutually. The width of the PSB in z-direction is small and, moreover, even when mass is accumulated here, it can expand freely. The surplus of mass will produce compressive stresses only in x-direction. Since PSB is continuously deformed plastically, these stresses will be continually relaxed and strain offsets in x-direction will arise. The strain offsets will produce extrusion at the site where the channel intersects the surface and intrusion at the site where the wall intersects the surface (Fig. 5a). The periodicity of extrusion-intrusion pairs can be derived from the periodicity of walls and channels. The average spacing s between the extrusions and intrusions is derived from the average spacing d between the walls according to relation (1).

The consequences of the flux of vacancies out of the PSB to the matrix and the flow of the atoms in the opposite direction are different. In this case, the mass accumulates in the whole PSB and since free expansion is possible only in z-direction, the whole PSB is extruded both in x- and y-directions. As a result a ribbon-like extrusion is produced. The extrusion of the whole PSB is compensated by the two intrusions at the interface between the PSB and the matrix.

Since vacancies in cyclic straining migrate both within the band and from the band to the matrix, both processes pass simultaneously and resulting relief should show both ribbon- and tongue-like extrusions and intrusions. The combination of both processes at a later stage of development results in ribbon-like extrusion whose height changes periodically and is accompanied by two intrusions at the interface with the matrix. It corresponds reasonably to the actual observations of the surface relief (see Fig. 2).

The same reasoning can be applied to persistent slip macroband [30] and a net protrusion connected with the macroband is predicted. This prediction is in agreement with experimental observations [17, 19].

Repetto and Ortiz [32] adopted the mechanisms of dislocation interactions and point-defect migration from PSB to the matrix and performed finite element modelling of extrusion and intrusion formation. Reasonable agreement with the experimental observations of the shape of ribbon-like extrusions and accompanying intrusions was obtained.

4.3 Models of crack initiation

Formation of the surface relief on the originally flat surface due to localised cyclic plastic straining represents the first step in the nucleation of a fatigue crack. Sharp intrusions represent an effective stress raiser since the radius of the intrusion is very small. The sharp corner technique developed by Basinski and Basinski [15] and the sectioning technique applied by Hunsche and Neumann [33] allow to estimate the notch radius to 0.1 μm. The stress and strain concentration in the tip of an intrusion is thus comparable with that of a crack of the same dimensions. The high stress concentration in the tip of an intrusion will give rise to local slip-unslip mechanism along the primary plane. The irreversible slip-unslip mechanism has been considered already by Wood [8]. The more specific model taking into account the line of alternating intrusions and extrusions at the emerging PSBs has been proposed by Polák and Liškutín [34]. Fig. 6a shows schematically the environmentally

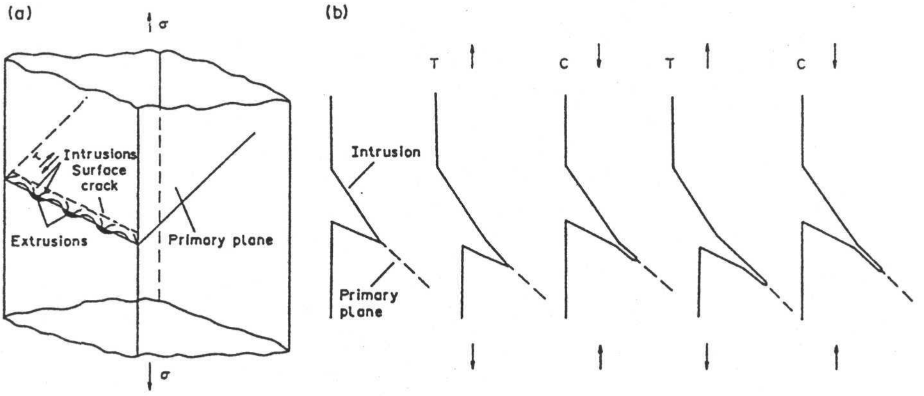

Fig. 6. Schematics of environmentally assisted crack initiation, a) nucleation of a shallow crack from a row of intrusions, b) irreversible slip-unslip.

assisted nucleation of a row of cracks from intrusions that link to create a shallow surface crack. Fig. 6b shows schematically the slip-unslip mechanism starting from the tip of an intrusion under the action of corrosive environment which prevents the rewelding of newly created surfaces. The mechanisms shown in Fig. 7 result in the formation of the shallow microcrack within PSB.

5. Effect of inhomogeneities and of inclusions on the fatigue crack initiation

The inclusions and inhomogeneities have profound effect on the initiation of the crack mostly due to the stress and strain concentration. Tanaka and Mura [35] analysed three basic types of crack initiation from an inclusion. They considered the crack from the debonded inclusion, a cracked inclusion by an impinging slip band, which can continue in the matrix, and a slip band emanating from an uncracked inclusion. In ductile materials the latest case is encountered most often. The mechanism of early crack nucleation is identical to that in homogeneous material provided local stress and strain fields are considered. The probability of crack initiation from constituent particles increases with the thickness of these particles.

6. Conclusions

Present models of fatigue crack initiation yield predictions of the surface relief formation and shallow crack formation in reasonable agreement with experimental observations.

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