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The Growth of Persistent Slip Bands During Fatigue

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ABSTRACT One of the early manifestations of fatigue is the appearance of persistent slip bands, some of which eventually become sites for fatigue cracks. This paper describes some of the first systematic quantitative observations of the early stages of growth of individual persistent slip bands (psbs) in polycrystalline materials. Specimens of 6061-T6 aluminium were fatigued in a specially constructed photoelectron microscope. The psbs are shown to consist of a periodic linear array of semicircular extrusions ~1 μm in diameter. Initially a single extrusion appears at a site within a grain. The psb elongates across the grain by the sequential addition of further extrusions. The psbs elongate rapidly at first and then more slowly, following a parabolic dependence on the number of fatigue cycles. A model is proposed based upon a periodic array of 'cells' in the psb, similar to the dislocation structures which have been observed in other materials. The model agrees with the experimental observations, provided that the cyclic strain amplitude in the psb is at least ten times that in the matrix of the grain.

Introduction

The earliest visible manifestation of metal fatigue is the development of surface deformation in the form of so-called persistent slip bands (psbs) within some of the grains of the metal (**1**)(**2**). These linear features are rendered visible by their profile, which in cross section consists of extrusions and intrusions. This profile can be very pronounced and is indicative of very severe localized deformation. Since this process eventually results in the formation of a fatigue crack, either along the grain boundary at the tip of a psb, or along the psb itself (**3**), it clearly plays an important role. Therefore, psbs have been studied very extensively by a variety of techniques. The following findings pertain to the present investigation.

(1) The cyclic strain within a psb is much greater than that in the surrounding matrix of the grain (**4**). This holds true not only for alloys but also for pure single crystals, where the creation of psbs correlates with a plateau in the cyclic stress–strain curve (**5**).
(2) The microstructure within a fully formed psb is quite different from that in the adjacent matrix. For example, transmission electron microscopy of precipitate-strengthened aluminium alloys has shown that the cyclic motion of dislocations effectively destroys small precipitates within the psb, so that it consists of a thin (~0.1 μm) planar layer of single-phase

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material **(6)(7)**. As another example, electron microscopy of pure single crystals shows that there is a marked difference in the dislocation structure between psbs and the matrix. Within the psb there are walls of dislocations arranged in patterns known as ladders and cells **(8)(10)** while in the adjacent matrix dislocations are more randomly dispersed. The presence of similar but less developed dislocation structures has also been reported in psbs in polycrystalline aluminium alloys **(6)(11)**.

(3) The above knowledge has been obtained primarily from post mortem examination of well developed psbs. There is much less information on the manner in which the psb forms. In particular there are hardly any measurements of the growth kinetics, which is in marked contrast to the extensive literature on the growth of fatigue cracks **(12)(13)**.

This paper describes measurements of the elongation of psbs in polycrystalline 6061-T6 aluminium by means of a photoelectron microscope equipped with a fatigue stage **(14)**. This technique is sensitive enough to detect the early stages of psb formation and is non-destructive so that it provides sequential information during a fatigue test. It will be shown that psbs appear on the surface as an approximately periodic linear array of small ($\sim 1\ \mu m$) extrusions. Initially a single extrusion forms. Then the psb elongates, with the addition of more extrusions, at a rate which varies inversely with its length. This behaviour is explained in terms of a concentration of the cyclic strain within the psb.

Experimental

Small specimens of 6061-T6 aluminium (1% Mg, 0.6% Si, 0.3% Cu, 0.2% Cr) were machined from sheet material 1.5 mm thick, with pancake shaped grains of average diameter $\sim 30\ \mu m$. On some of the specimens the surface to be examined was mechanically polished, to aid subsequent examination by conventional microscopy. The majority were studied with the as-received surface texture. All the specimens were degreased with acetone and cleaned by immersion in chromic acid at 75°C for five minutes. After rinsing with water and alcohol, they were anodized in a 3 per cent solution of tartaric acid at a potential of 10 volts to form a surface oxide film 14 mm thick.

The geometry of the specimens for the photoemission electron microscope (PEM) is shown in Fig. 1. These specimens were fatigued by reverse bending *in vacuo* (10^{-3} Pa) in the specimen chamber of the microscope, to produce surface maximum cyclic strains of $\pm 3.0 \times 10^{-3}$. In the photoemission electron microscope, the specimen is illuminated by ultraviolet radiation and electrons emitted from the specimen form a magnified image of the surface on a fluorescent screen. As the specimen is fatigued, the emergence of psbs ruptures the anodic oxide film exposing the fresh metal surfaces of the extrusions. This extruded material emits much more intensely, creating the white spots or lines in the photoelectron micrographs shown in the next section. This phenomenon is also known as exoelectron emission **(14)**.

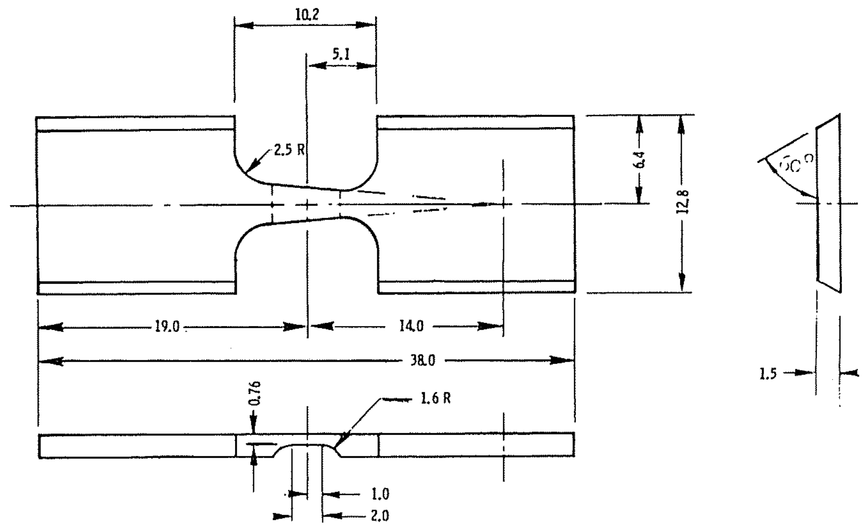

Fig 1 Geometry of specimens used in the photoelectron mciroscope (dimensions in mm)

Results

The photoelectron micrographs in Fig. 2 were obtained at intervals during the fatigue cycling of an unpolished specimen. The three long straight lines of emission in these micrographs correspond to fiducial scratches, which identify the location on the surface of the specimen and provide a calibration of magnification. This sequence shows the development of many sources of intense emission, where the 14 nm oxide film has been ruptured by emerging psbs. A distinctive feature is that each psb appears initially as a small spot of exoelectron emission and subsequently elongates with continued fatigue cycling. This behaviour is clearly illustrated by the three psbs labeled A, B, and C. The positions of these psbs were measured with respect to the fiducial scratches, so that their point of initiation could be identified in subsequent micrographs. These initiation points are marked by the tips of the arrows in Fig. 2(f). In each case the psb elongated in both directions, showing that it originated somewhere in the interior of a grain.

The growth of these three psbs is summarized quantitatively in Fig. 3, which shows that the length of each psb increased as the square root of the number of fatigue cycles. The psb at A grew the most slowly despite having been the first to emerge, while psb C apparently experienced some resistance to growth at the very beginning.

Essentially identical results to the above were also obtained from polished specimens and have been reported elsewhere **(15)**. Subsequent examination of both polished and unpolished specimens in a scanning electron microscope

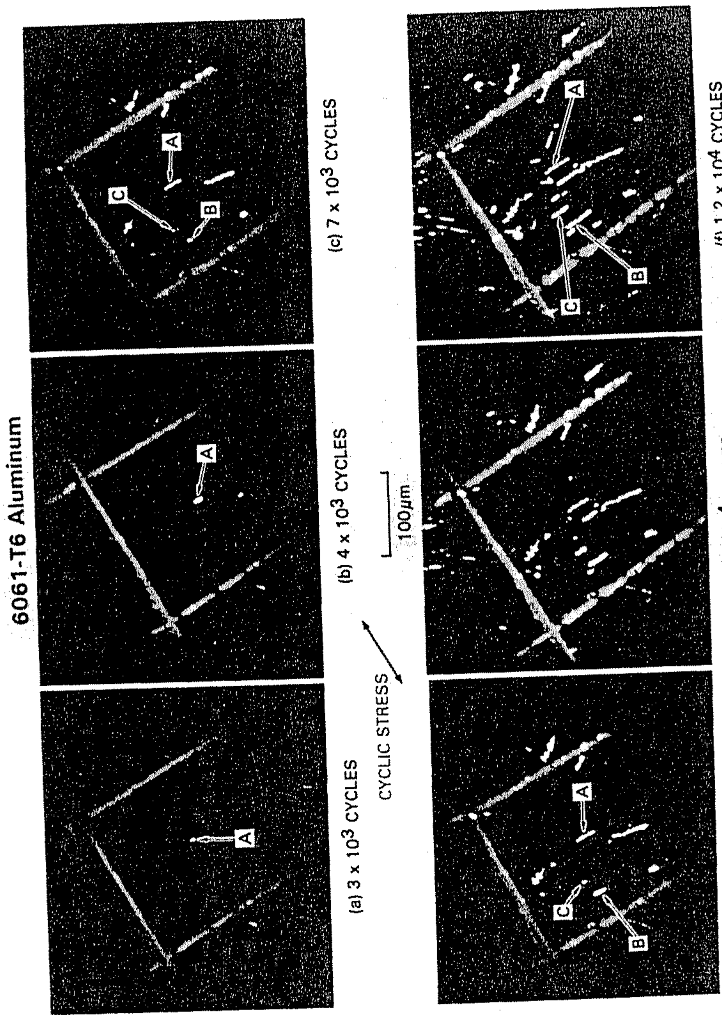

Fig 2 **Photoelectron micrographs showing development of exoelectron emission from psbs produced by fatigue of an unpolished specimen**

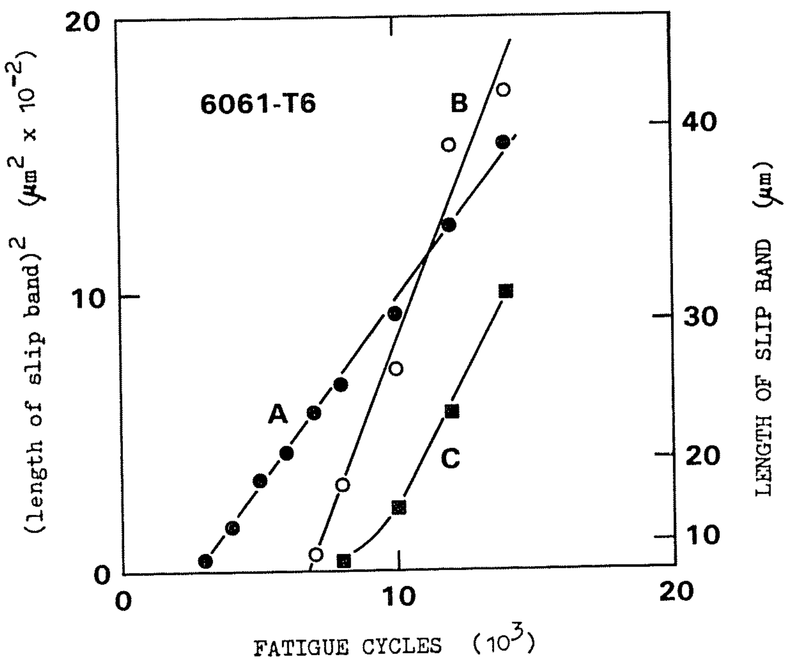

Fig 3 **Effect of fatigue cycles on the square of the length of slip bands A, B, and C, shown in Fig. 2**

(SEM) revealed that the psb extrusions were nearly identical in appearance. However, the polished specimens were of advantage in that the extrusions could be seen more clearly in the SEM. An example is provided by the scanning electron micrograph in Fig. 4, which shows two psbs consisting of quite regular arrays of individual extrusions. These extrusions are seen more clearly at higher magnification in Fig. 5, each one measuring ~1 μm parallel to the psb. This periodicity was evident on a large number, but not all, of the psbs; it tends to be masked in the later stages of growth when the extrusions become more pronounced. (This process has just started on an extrusion at the lower right in Fig. 5.) On the other hand, in the early stages of growth when a psb is still scarcely visible in the SEM, it often appears as a pair of spots in the PEM (i.e., there are already two extrusions). Thus, this perodicity seems to be an inherent feature of the psbs, and elongation occurs by the sequential addition of individual extrusions.

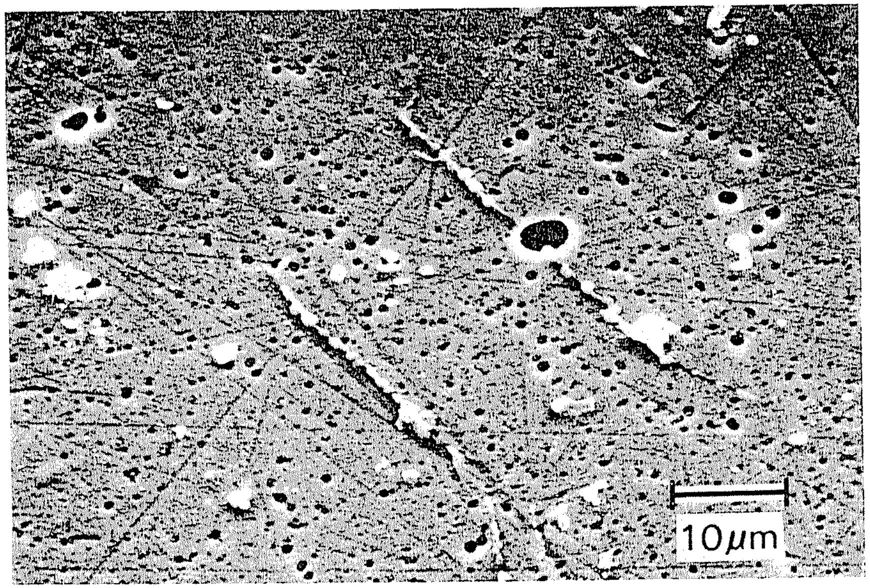

Fig 4 Scanning electron micrograph showing the array of extrusions on two psbs

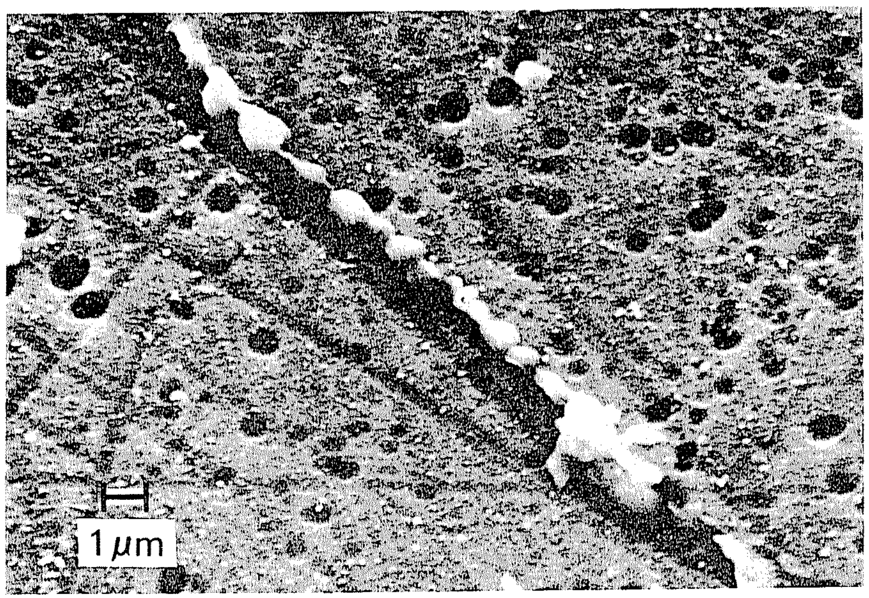

Fig 5 Scanning electron micrograph showing an enlarged view of the lower psb in Fig. 4

Discussion

Let us now consider the above findings in more detail.

1. Extrusions

The periodic nature of the extrusions (Fig. 4) is not considered to be unique to this alloy, since an identical periodicity has been reported in iron (**16**). This periodicity shows that within the psb there must be an array of barriers to dislocation motion with a spacing of ~1–2 μm. Unfortunately, transmission electron micrographs of the dislocation structure in psbs in 6061-T6 aluminium are not available at the present time, but a dislocation cell structure has been observed in iron (**16**) and other aluminium alloys (**6**)(**11**) and the cells are typically ~1–2 μm across. In addition, the extrusions are not unlike those observed by Laufer and Roberts (**10**) on single crystals of copper, and which they correlated directly with the sub-grain or dislocation cell structure of the psbs. Thus, there is circumstantial evidence to suppose that such a 1–2 μm cell structure is also present in the psbs in 6061-T6 aluminium, and that the periodic extrusions mark the presence of these cells.

2 Elongation process

The initial formation of a single extrusion, followed by the systematic addition of other extrusions, shows that the 'cell' structure is developing either in concert with, or shortly before, the appearance of the individual 'single cell' extrusions. Thus, the location of the initiatory 'cell' and extrusion is probably determined by either an inherent weak spot or stress concentration within the grain, where deformation occurs preferentially. At that site we can expect dispersal of the strengthening precipitates and a build up of dislocation density. It can then be visualized that the dislocation density in that region may increase to the point of instability, so that it is energetically favourable for the dislocations to rearrange into a cell structure, by a mechanism such as that proposed by Kuhlmann-Wilsdorf and Nine (**17**). Once the initiatory cell has formed, the sudden ease of dislocation motion within the soft interior of the cell can now result in the rapid growth of the first extrusion. By the time this initiatory cell has produced a small extrusion, say ~100 nm high, ~300 dislocations will have arrived at the side walls of the cell. This is far too many to be accommodated in a pile up, so the associated stresses will promote the emission of dislocations from the cell walls into the adjacent matrix material of the grain. This flux of dislocations will again produce localized changes in the microstructure of the matrix, so that the process will be repeated. In this way the psb will grow into a two dimensional array of cells with an associated array of surface extrusions.

3 *Rate of elongation*

The length (l) of a psb increases with the number of fatigue cycles (N) in accordance with the relation

$$L^2 \sim (N - N_o) \tag{1}$$

where N_o is the number of cycles required to produce the first extrusion. Thus, the rate of elongation is of the form

$$\frac{dl}{dN} \sim l^{-1} \tag{2}$$

Thus, the rate at which the new cell and associated extrusion are generated at the tip of a slip band decreases as the slip band elongates.

To account for this behaviour we will start with a simple two phase model (psb and matrix) of the type used previously to describe the cyclic stress strain curve (**18**). According to this model the cyclic strain is not uniformly distributed throughout a grain because the interior of the psb is known to be softer than the matrix. However, the cyclic strain in the psb (ε_c) is assumed to be uniform, i.e., the cells are all the same and the uniform deformation occurs in the soft interior of each of the cells. In addition, we will assume, based upon the physical process of psb elongation outlined above, that

$$\frac{dl}{dN} = \beta\varepsilon_c \tag{3}$$

where β is a constant.

Consider a grain of diameter D in the surface of the specimen which has developed a psb of length l and thickness t. In a constant displacement fatigue test, as in these experiments, the total surface cyclic strain (ε_T) accommodated by the grain is constant and is usually perpendicular to the slip band (see, for example, slip bands in Fig. 2).

Applying a simple rule of mixtures

$$\varepsilon_T = f_c\varepsilon_c + (1 - f_c)\varepsilon_g \tag{4}$$

where ε_g is the cyclic strain in the matrix of the grain, and

$$f_c = tl/D^2 \tag{5}$$

is the areal fraction of the grain occupied by the psb. Combining equations (4) and (5) yields the following expression for the cyclic strain within the psb

$$\varepsilon_c = \frac{D^2}{tl}(\varepsilon_T - \varepsilon_g) + \varepsilon_g \tag{6}$$

Substituting in equation (3)

$$\frac{dl}{dN} = \frac{\beta D^2}{tl}(\varepsilon_T - \varepsilon_g) + \beta\varepsilon_g \tag{7}$$

The first term in this equation is of the same form as the empirical equation (1). Indeed if the second term can be ignored, integration yields

$$l^2 = \frac{2\beta D^2}{t}(\varepsilon_T - \varepsilon_g)(N - N_o) \tag{8}$$

This equation is consistent with the results plotted in Fig. 3. Thus, it may be concluded that the first term in equation (6) is dominant. This term is simply that portion of the cyclic strain within the psb which is in excess of the cyclic strain experienced by the rest of the grain (ε_g). In other words, it is the process of strain localization within the psb that controls the elongation of the psb.

For typical values of $D = 50\ \mu$m and $t = 0.1\ \mu$m, the geometrical strain concentration factor D^2/tl in equation (6) is $\sim 10^4$ for the initial extrusion, and decreases only to 500 by the time the psb extends across the grain (i.e., when $l = D$). Thus, $\varepsilon_c \gg \varepsilon_g$ even for small values of $(\varepsilon_T - \varepsilon_g)$; i.e., the strain in the psb is very large and controls the elongation process but contributes very little to the total strain ε_T.

Finally, from Fig. 3 we see that the parabolic growth relationship holds for $l \leq 40\ \mu$m. Thus, even at the end of these observations $\varepsilon_c \sim 10\varepsilon_g$ or $\varepsilon_c = \pm 3 \times 10^{-2}$. When only the first cell and extrusion were formed, $l \sim 2\ \mu$m and $\varepsilon_c \sim \pm 6 \times 10^{-1}$.

Conclusions

The following picture emerges from these measurements and modelling of the growth of persistent slip bands in 6061-T6 aluminium.

(1) The psb appears as a linear array of surface extrusions with a periodicity of ~1 to 2 μm.
(2) The psb elongates by the addition of further extrusions, the total length increasing as the square root of the number of fatigue cycles.
(3) Each extrusion is thought to be associated with a characteristic cell in the microstructure of the psb.
(4) The cyclic strains (ε_c) within the psb are very large, encompassing a range of 10–100 times greater than the applied macroscopic strain.
(5) The value of ε_c decreases as the psb elongates.
(6) The cyclic strain in the leading cell at the tip of a psb ejects a high density of dislocations into the adjacent material, which in some manner creates a new cell and associated extrusion.

Acknowledgements

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