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The observation and analysis of the dislocation morphology of fatigue crack tips at steady state propagation rates subject to a single peak load

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Abstract

During fatigue crack propagation there is large interaction effects of the fatigue cycle for different loading amplitudes. Two examples are the retarding effect of overload and the accelerating effect of underload on the crack propagation. In the former, the result is explained in terms of residual stress effects associated with the overload, and in the latter, the underload partially annihilates the residual stress built up by the positive load. However, at the microstructure level of material under fatigue, the crack propagation is caused by dislocation action. Assuming this, this paper reports studies of the crack propagation interaction effect by using microstructural examination of crack tips. Observations were made with the Back Electron Images (BEI) of the Scanning Electron Microscope (SEM). The results are: (1) the microstructure of cells close to the crack tips formed into vein or loop patch structures upon the overload, so that the crack propagation was reduced. (2) The region of cells s close to the crack tips become enlarged on the underload and the scale of the other microstructure (such as PSB, vein and loop patch) were also enhanced too, so that the crack propagation was accelerated.

Keywords: Fatigue crack tips; Steady state propagation rates; Single peak load

1. Introduction

In the process of the fatigue fracture, regardless of the crack initiation or crack propagation, all the dislocation interaction occurs in the interior of the material [1]. For example, consider a crack initiated in the persistent slip band (PSB) accompanying a ladder-like wall dislocation structure embedded in the PSB [2–4], and initiated at an interaction between the persistent slip band and the grain boundaries(PSB-GB) accompanying the dislocation cell structure [5,6]. At high crack propagation rates, the dislocation morphology in front of the crack tips is usually cell structure [7–11]; and at low crack propagation rates, the dislocation morphology ahead of the crack tips is cellular in a small region, but then followed by a ladder-like wall of the PSB, vein and loop patch structure [12].

However, the true condition of loading in the process of fatigue crack propagation is non-homogeneous. In other words, the loading may shift between overload or underload in the loading history. Therefore, the overload or underload will influence the rate of crack propagation. In the condition of overload, the crack behavior will retard the propagation rate [13–21], and in the case of underload, the crack behavior will accelerate the propagation rate [20]. From the theory of strength, the explanation of this phenomenon is that the retardation or acceleration of the crack propagation rate because of overload or underload is due to plasticity strain inducing a residual stress in the region ahead of the crack tips. During the overload condition, the residual stress results in crack tip closure, while the underload partially annihilates the residual stress built up by the positive load.

The results of Huang et al. [22] described the microstructures in front of the crack tip at various propagation rates. The dislocation morphologies around the fatigue crack tip at a crack propagation rate of 10^{-6} mm

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per cycle were examined, an example of which is shown in Fig. 1 [22]. Within a 3-μm distance of the crack tip, misorientation cells and the following neighboring dislocation cells were observed extending to 10 μm, both with an average diameter of 0.7–0.8 μm. Next to these cells were different types of walls and PSBs corresponding to the degree of accumulation of local plastic strain. Condensed walls occupied an area only 10 μm wide, beyond which, were PSBs with multiple-directional ladder-like dislocation walls and, following, single-directional ladder-like dislocation walls occupying the next 50 μm. Outside the ladder-like PSBs, 120 μm away from the crack tip, were vein structures and loop patches corresponding to very low local plastic strain amplitudes resulting from the fatigue strength close to the fatigue limit [23,24]. This observation indicated that the strain field of the crack tip subjected to a crack propagation rate of 10^{-6} mm per cycle was sufficient to develop full evolution of various kinds of dislocation structures in addition to dislocation cells at the crack tip.

When the crack propagation rate was decreased to 10^{-7} mm per cycle, dislocation morphologies in front of crack tip did not change much except for the decrease of the volume percentage occupied (Fig. 2) [22]. The dislocation cells were still limited to within 3 μm in range with an average diameter of 0.7–0.8 μm. Condensed walls were seldom seen. In most cases, PSBs with multiple directional ladder-like dislocation walls extended to 3 μm in range next to the cells and the following single directional ladder-like dislocation walls occupied the next 12 μm. Veins and loop patches extended to the neighboring grains.

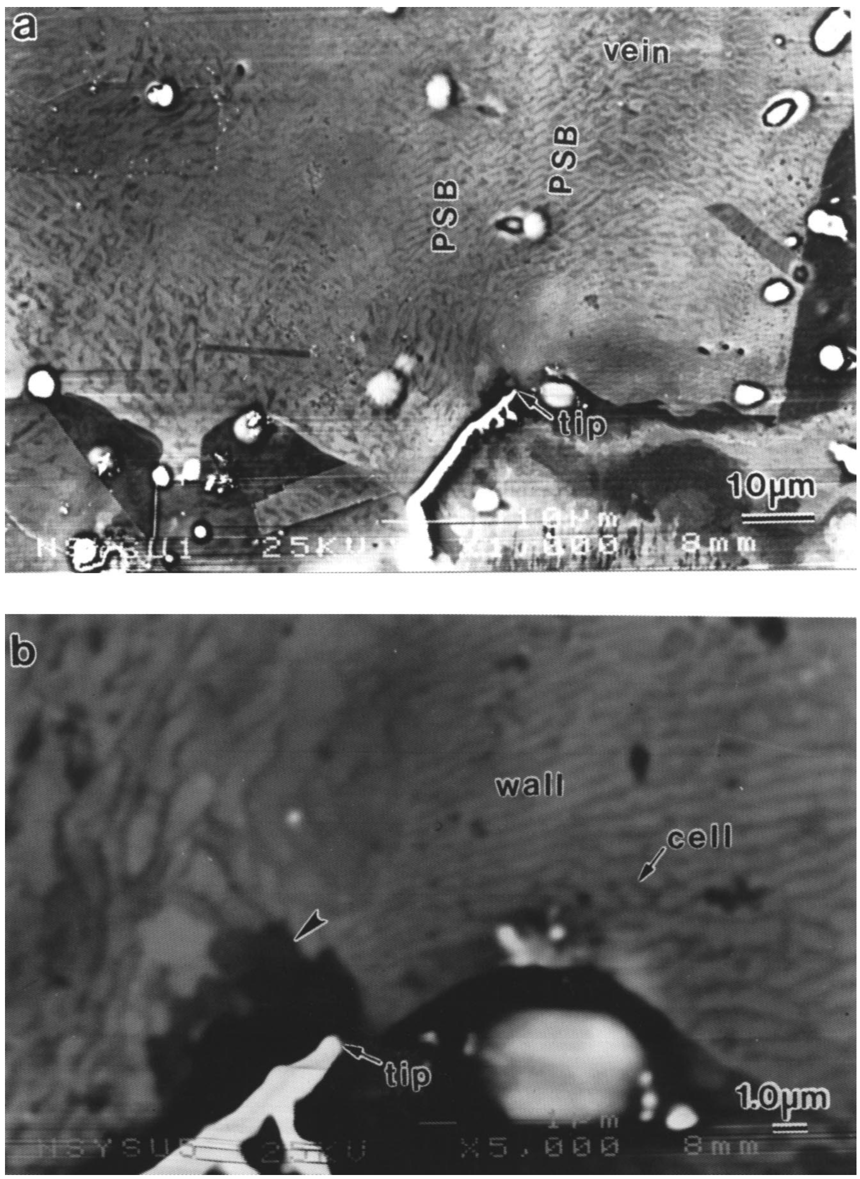

Fig. 1. (a) The dislocation structure close to the crack tip is following as misorientaion cell, cell, wall, PSBs, vein and loop patch structure at the crack propagation rate of 10^{-6} mm per cycle. (b) Showing misorientated cells adjacent to the crack (index arrow) [22].

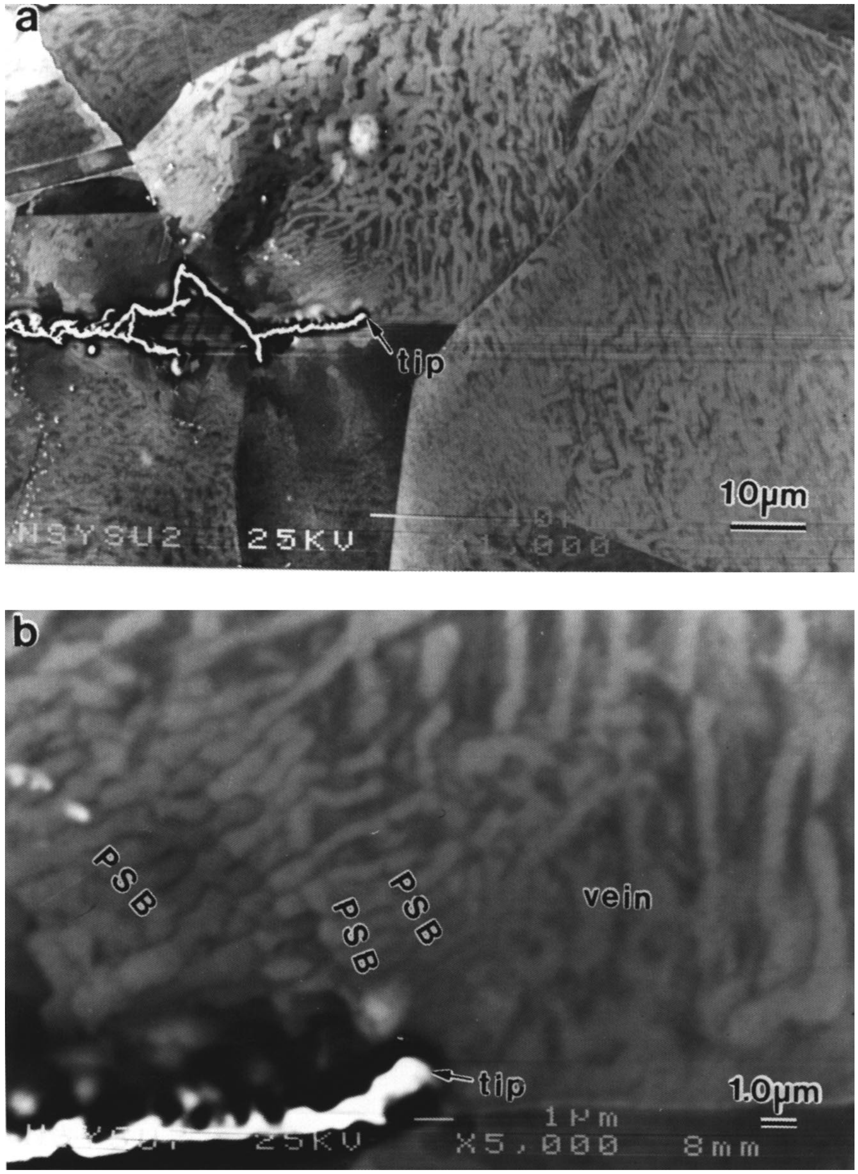

Fig. 2. (a) The dislocation morphologies near the crack tip is following as, cell, PSBs embedded in vein or loop patch, vein and loop patch structure at a propagation rate of 10^{-7} mm per cycle. (b) The multiple ladder-like wall structures at a distance about 4 μm from the side of crack path and about 3 μm from the crack tip in the forward direction [22].

In the results of the strain field for a propagation rate of 10^{-7} mm per cycle, the total region occupied by cells and PSBs decreased to 20 μm compared to 120 μm for the sample subjected to a propagation rate of 10^{-6} mm per cycle. Although the decay of the plastic zone is significant, dislocation cells with the size of 0.7–0.8 μm and the region of 3 μm were almost the same. This indicated that the crack could still be propagated. Nevertheless, slower propagation rates may be due to more cycles to evolve enough regions for condensed walls (a step from PSBs to cells at low strain amplitude [25]).

When the rate of crack propagation was decreased to 10^{-8} mm per cycle, dislocation morphologies in front of crack can be shown Fig. 3 [22]. The dislocation structure at the crack was cell and next to the multi-directional PSB, and is similar to that for the propagation rate of 10^{-7} mm per cycle. The above results point out that regardless of the rate of crack propagation, the dislocation structure at the crack tip is cell with an average diameter of about 0.7 μm. At the same time, the rate of the crack propagation is determined by whether the dislocation structure in front of the crack tips is fully evolved with a region of extension of dislocation structures close to the crack tips evolving into cell structure with an average diameter about 0.7 μm.

We believe that only difference between overload and underload is whether the cellular region is wide or narrow. This study used the single compact tension specimen of copper to follow the crack propagation until the rate of crack propagation reached a specific steady

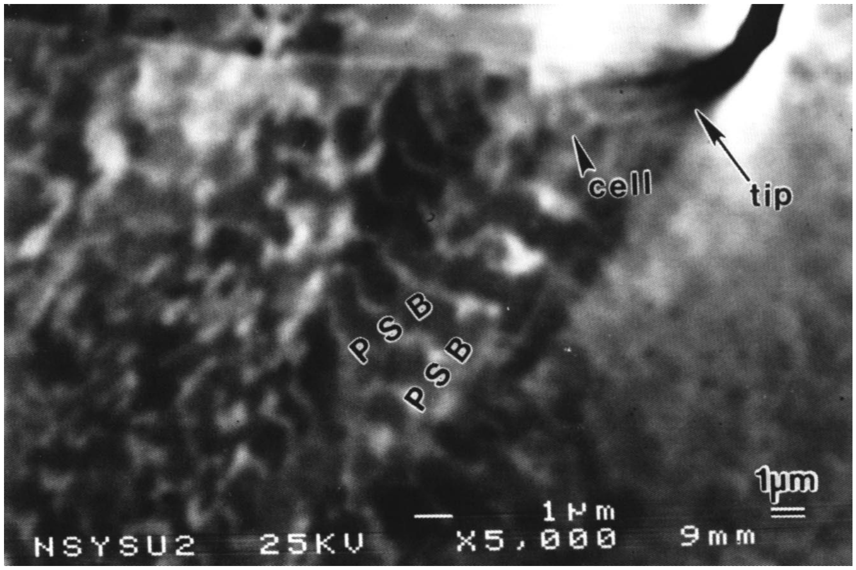

Fig. 3. The dislocation structure in front of the crack tip is following as, cell, PSBs embedded in vein or loop patch, vein and loop patch structure at the crack propagation rate of 10^{-8} mm per cycle [22].

state, and then subject to a peak overload or underload. Finally, the BEI of the SEM was employed to observe the microstructure in front of the crack tips. The purpose of studying dislocation morphology variation is to elucidate the changes in the crack propagation rate.

2. Experimental

A plate of high purity polycrystalline copper(99.95%) was used in this study. The specimens were annealed at 850°C for 2 h in a vacuum of 10^{-5} Torr and then cooled in the furnace. The grain sizes of the specimens were about 60–80 μm. The preparation of specimens followed the instruction of ASTM E647 for a single edge compact tension specimen. The crack propagation was induced by a computerized Instron 1332 hydraulic testing machine at $R=0.1$ (stress ratio, $R=P_{min}/P_{max}$) at a frequency of about 20 Hz. During crack propagation at each step, the cracks increased by a length of 0.254 mm with the effective load reduced by 5–8% of the previous step. The crack length was measured by a traveling microscope to an accuracy of ± 0.01 mm. In this study, when the crack propagation reached a special steady state the specimen was then subjected to an overload or underload, after which the crack propagation was stopped. The loading history is indicated in Fig. 4. The stress intensity (ΔK) was determined from ASTM E647 as:

$$\Delta K = \Delta P/(Bw^{0.5})f(a/w)$$

where: $f(a/w) = [(2 + a/w)(0.866 + 4.72(a/w) - 5.56(a/w)^2 + 13.32(a/w)^3 - 14.72(a/w)^4)/(1 - a/w)^{1.5}$; B: thickness; a: crack length; w: effective width; ΔP: range of loading, $\Delta P = P_{max} - P_{min}$.

There are two parts to the experimental design. The first part, to make sure that after the rate of crack propagation is stabilized at steady state, the application of a peak of overload or underload causes crack propagation acceleration or retardation. The other part is to obtain an observational sample from a specimen subjected to an overload or underload, in order to examine the microstructures. After the specimens were subjected to a peak of overloading or underloading, then the specimens were divided two parts. The one part is taken back to the original loading condition to continue crack propagating in order to observe the phenomenon of the acceleration or retardation. The other part is the stop crack propagation to prepare the sample of the SEM for observation of the microstructures in front of the crack tips. In addition to that mentioned above, the application

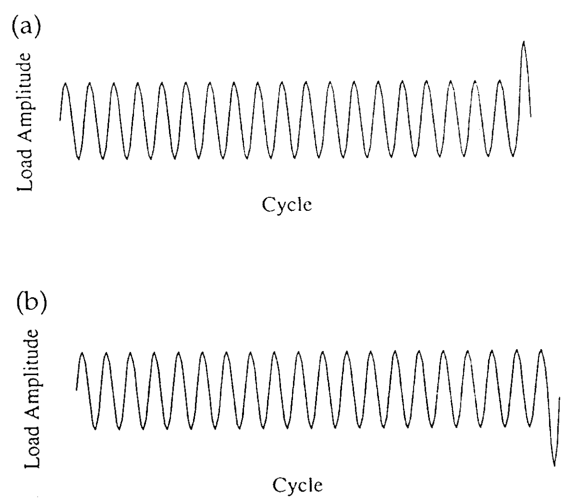

Fig. 4. The loading history of the crack propagation. (a) Overload. (b) Underload.

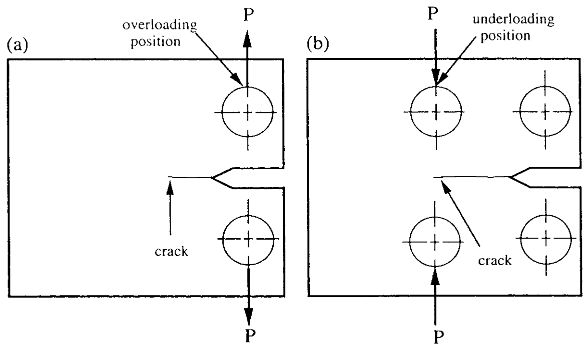

Fig. 5. Schematic diagrams of the loading position. (a) Overloading. (b) Underloading.

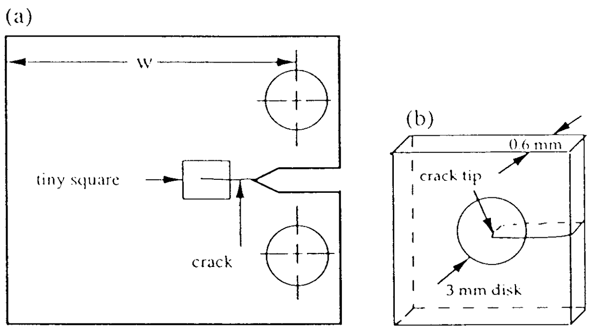

Fig. 6. Schematic diagrams of the foil preparation. (a) Position of tiny square. (b) Position of discs.

of a peak of underload condition is action on the upside of crack tip. The position of overloading and underloading is shown in Fig. 5.

To observe the dislocation morphologies at the crack tip under a variety of crack propagation rates, the fatigue specimens were cut into tiny squares of 10 mm that contained a crack longer than 3 mm (as shown in Fig. 6(a)); the squares were then cut into slices of 0.6 mm thickness. The slices were then ground to a thickness of 0.15–0.2 mm by sand paper and then punched into disks of 3 mm in diameter (as shown in Fig. 6(b)). The 3-mm disks were twin-jet polished using Sturus D2 polishing solution at 5–7 V and 5–10°C. A JEOL 6400 SEM was used to investigate the microstructures at the crack tip and the crack path by means of BEI [26]. The accelerating voltage was set at 25 KV, and the working distance was 8 mm.

3. Results

The phenomenon of the acceleration or retardation of crack tip propagation when the crack tip is subjected to a peak of overload or underload at steady state of loading is shown in Table 1. It is clear that the rate of crack propagation is retarded after the crack tip has been subjected to a peak of overload at steady state of loading, and the crack tip is applied a peak of underload at steady state of loading is accelerated for pure copper. The dislocation morphology at the crack tip with a propagation rate of about 5×10^{-6} mm per cycle subjected to a peak overload (420 kg) is shown in Fig. 7 (the crack propagation rate retardation to 3.0×10^{-6} mm per cycle). In Fig. 7(a), the low magnification of the dislocation structure at the crack tip reveals a dislocation morphology that is almost a vein or loop patch structure. Fig. 7(b) is a higher magnification of Fig. 7(a). This distinctly exhibits the dislocation vein structure near the crack tips under a condition of overload. The Fig. 8 is taken from the other slice, which the loading condition is the same as Fig. 7. It is shown that the dislocation structure in front of the crack tips is loop patch structure. At the same time, the dislocation morphology is close to that of crack tips with a propagation rate of 10^{-7} mm per cycle subjected to a peak underload, as seen in Fig. 9 (subject to a compressing load about 180 kg and the rate of crack propagation accelerate from 3.0×10^{-7} to 5.0×10^{-7} mm per cycle) and 10 (subject to a compressing load about 360 kg and the rate of crack propagation accelerate from 6.7×10^{-7} to 1.3×10^{-6} mm per cycle). The difference between Figs. 9 and 10 is that the crack tip is subjected to an underload that the magnitude is one time of loading in the former, but the crack tip is subjected to an underload which the magnitude is double times of loading in the latter. The dislocation morphology in front of the crack tips after overloading of one time of loading is shown in Fig. 9. It indicates that within a 20 μm distance of the crack tip, the dislocation structures were cellular, wall-like, and had the multi-di-

Table 1
The crack propagation of retardation or acceleration after subject to a peak of overload or underload in steady state of loading
+: overloading; −: underloading.

Test point	Division				
	Steady loading (kg)	Steady propagation rate (mm/cycle)	Subjected to a peak loading (kg)	Propagation rate of change (mm/cycle)	Acceleration or ratardation
A	220	6.7×10^{-6}	+440	4.2×10^{-6}	retardation
B	130	1.2×10^{-6}	+260	4.7×10^{-7}	retardation
C	170	2.6×10^{-7}	−170	4.5×10^{-7}	acceleration
D	170	5.3×10^{-7}	−340	1.7×10^{-6}	acceleration

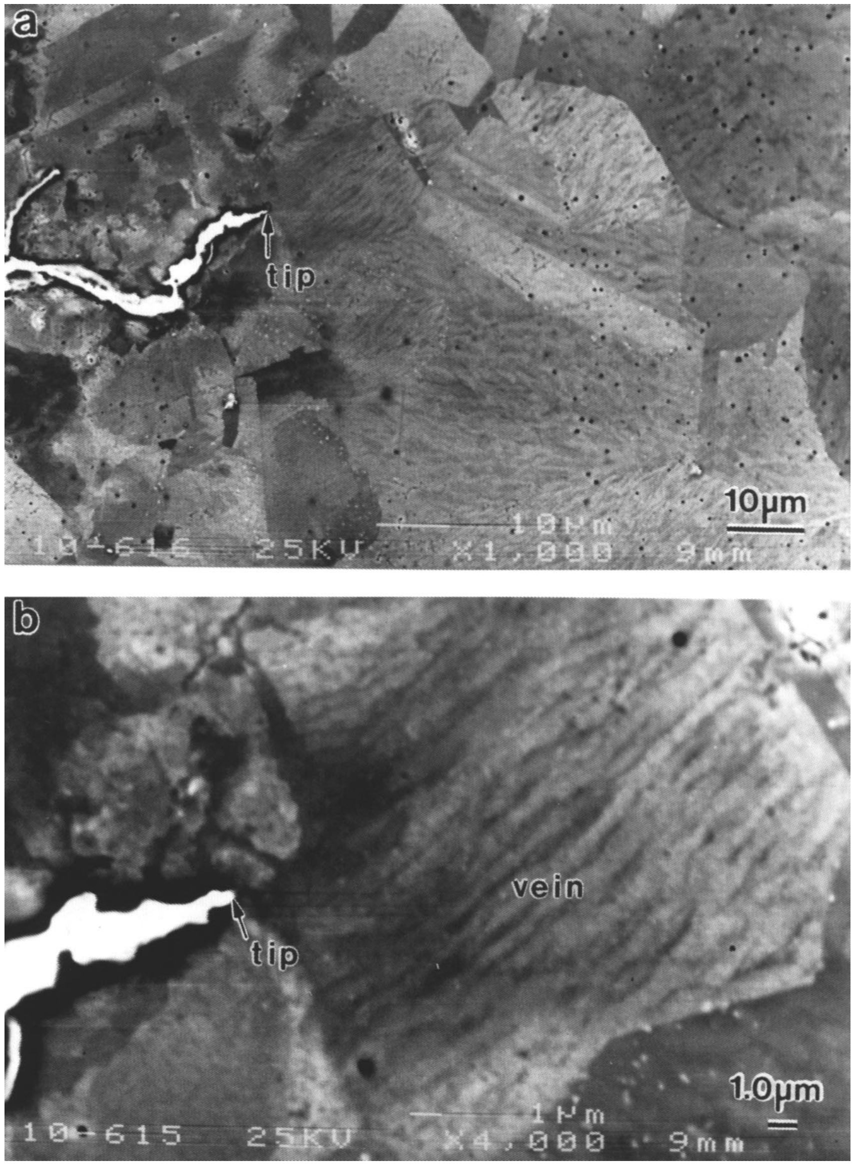

Fig. 7. The dislocation vein structure ahead of the crack tip at a propagation rate of 10^{-6} mm per cycle under overloading. (a) The low magnification. (b) The high magnification.

rectional ladder-like wall of PSB embedded in vein structure. At the same time, the high magnification of the microstructure close to the crack tips reveals that the dislocation structure in front of crack tips was obviously composed of dislocation cells with an average diameter of about 1.0 μm. Moreover, the dislocation morphology in front of the crack tip after overloading of double times of loading is cellular in structure with an average diameter larger than 0.7 μm (Fig. 10(a)). In Fig. 10(b), it can be seen that the dislocation structure exhibits multiple slip system in the vein structure to create the checkerboard block next to the cell region and around the crack tip.

4. Discussion

4.1. The microstructure at steady state propagation rate

As seen in Figs. 1 and 2, the dislocation morphologies close to the crack tips are all cellular. In other words, no matter what the crack propagation rate is, the dislocation structure in front of the crack tips is cellular with an average diameter of about 0.7 μm. However, although the microstructure ahead of the crack tips with various crack propagation rates is similar — such as cell, wall, ladder-like wall of PSB, vein and loop patch structure —

the size of the regions occupied by the various dislocation morphologies differs. This is due to the variety of plastic strain amplitude next to the crack tips to induce the change of the crack propagation rate.

According to the above discussion, for polycrystal copper to maintain the crack propagating, the dislocation in front of the crack tips must be cellular. However, in comparing dislocation structure areas between cracks with a 10^{-6} mm per cycle propagation rate and 10^{-7} mm per cycle propagation rate, we see that the area is larger in the former than in the latter. This indicates that the crack propagation rate is determined by the size of the dislocation structure: this structure in front of the crack tip forms into a cellular structure with cells of 0.7 μm average diameter. Moreover, under a steady state crack propagation rate, the regions of dislocation morphologies in front of the crack tips have a constant magnitude size. Based on these considerations, a specific constant propagation rate of the crack tips requires that the propagation rate change under the condition of overload or underload in the loading history, which can be explained by the variation of the range of the dislocation region ahead of the crack tip.

4.2. The microstructure at crack tip subject a single peak overloading

The specimen was subjected to a single peak overload (420 kg) after the propagation rate(about 5.0×10^{-6} mm per cycle) was stabilized. The rate of crack propagation was retardation from 5.0×10^{-6} mm per cycle to 3.0×10^{-6} mm per cycle. The dislocation structure next to the

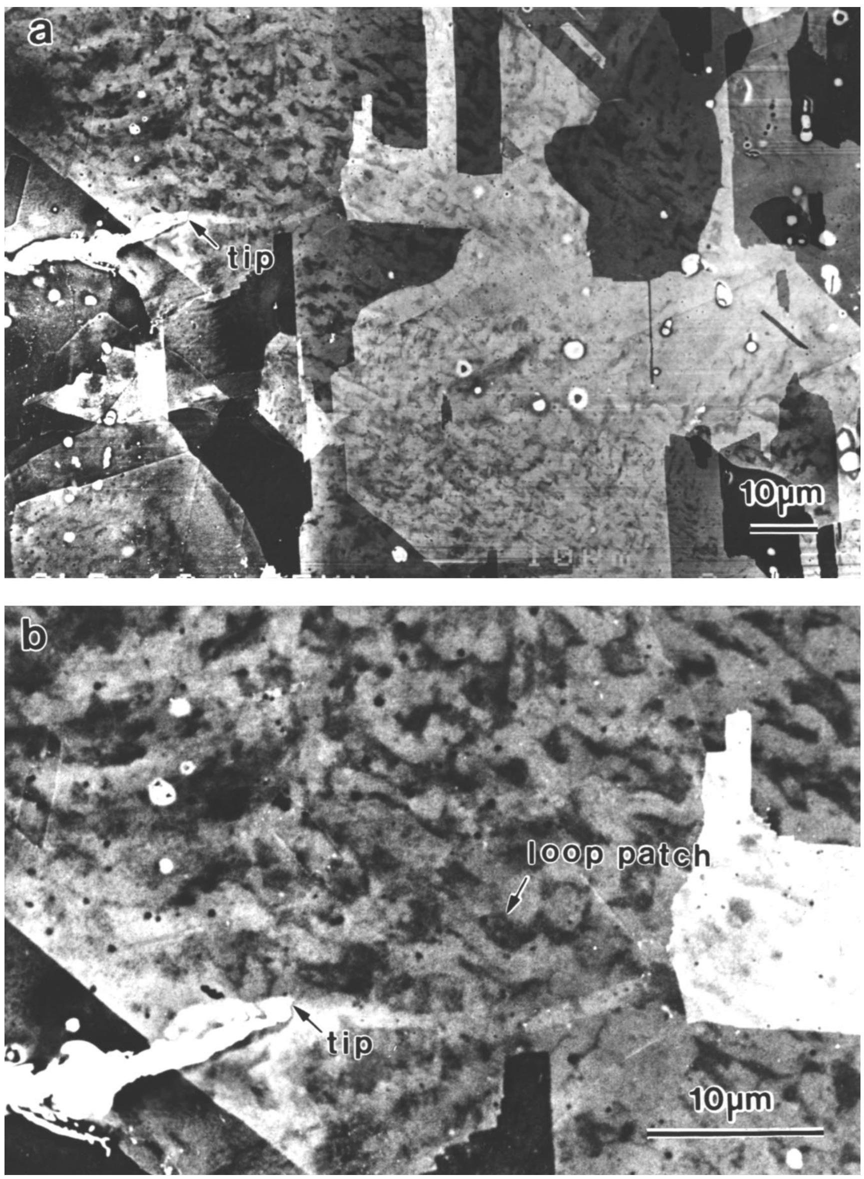

Fig. 8. The dislocation loop patch structure ahead of the crack tip at a propagation rate of 10^{-6} mm per cycle under overloading. (a) The low magnification. (b) The high magnification.

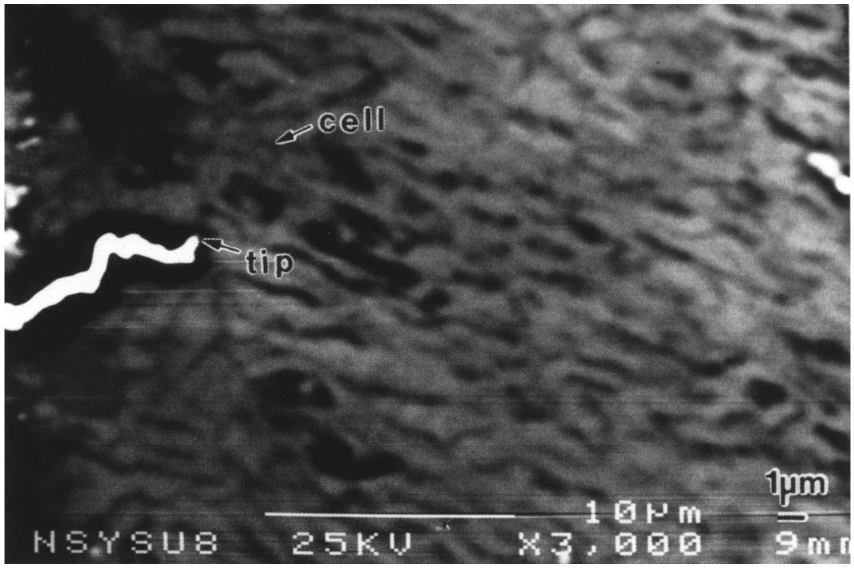

Fig. 9. The dislocation of vein structure in front of the crack tips at a propagation rate of 10^{-7} mm per cycle under the condition of loading with one time of overloading.

crack tips is transformed from that seen in Fig. 1 — the dislocation morphology at the crack tip with a 10^{-6} mm per cycle propagation rate fully evolved, i.e., showing misorientation cells, cells, walls, ladder-like walls of PSB, veins and loop patch structures into that seen in Fig. 7 (crack propagation rate is about 3.0×10^{-6} mm per cycle) — the dislocation close to the crack tip being veined in structure. In literature reports, the rate of crack propagation was also found to be retarded when the crack tip was subjected to a single peak overloading [13–21]. Based on Table 1, the crack propagation rate retardation of the test point B (the rate of retardation from 1.2×10^{-6} to 4.7×10^{-7} mm per cycle) is larger than point A (the rate of retardation from 6.7×10^{-6} to 4.2×10^{-6} mm per cycle). Because the loading amplitude of point A (220 kg) was higher than point B (130 kg), the accumulation of plastic strain of point A is faster than point B. Therefore, the dislocation evolution into cell structure, which is necessary for crack propagating, is faster at point A than at point B. At the same time, the other slice has the same as loading condition of Fig. 7. The dislocation structure in front of the crack tips is loop patch structure in Fig. 8. These results reveal that the dislocation ahead of the crack tips is vein or loop patch structure at an application overload is uniform. For the easy illustration of the phenomenon of retardation of crack propagation at the crack tip subjected to a peak overloading, the schematic status of crack propagation and amplitude of plastic strain is shown in Fig. 11. In Fig. 11(a) (the dislocation structure before overloading), the dislocation morphology at the crack tip with a 10^{-6} mm per cycle propagation rate is fully evolved. Whereas, in Fig. 11(b), the dislocation structures after overloading, exhibits the vein or loop patch in front of the crack tips. Because of the same propagation rate in the case of overloading, the amplitude of the plastic strain at the crack tip was enhanced several times with steady state propagation rate. Therefore, under this condition, the dislocation in the original cell structure as shown in Fig. 11(a) (Fig. 1) was quickly evolved into a cell structure with an average diameter of about 0.7 μm. Even the dislocation of walls and ladder-like walls of PSB has also developed into the dislocation cell structure due to the high plastic strain amplitude that induces the multiple slip system [27], thus satisfying the crack propagation need, and the crack tip progress. Nevertheless, in compliance with the theory of strength, the concentration factor of plastic strain decays quickly at a distance far away from the crack tip. Hence, the region of the plastic strain, which accumulates faster than the original state, is constrained in a distance far away from the crack tip. In other words, out of this range, the increase of plastic strain amplitude is little affected by the strain concentration factor even if equal to zero (Fig. 11(c)). Comparing the accumulation of plastic strain between before overloading and after overloading, the increase of plastic strain accumulation is too small to change the dislocation structure. Thus, the dislocation morphologies remain in their previous status (before overloading). Consequently, the dislocation structures located at the tip is then incompletely developed (Fig. 11(b)). Moreover, according to the theory of strength, the crack propagation rate of the tip will be retarded under the condition of overload, and this means that the plasticity strain of the crack tip induces the residual compressing stress increase to close the crack tip. The results from Figs. 1 and 2 indicate that in order to maintain crack propagation, it is necessary that the dislocations ahead of the crack tip need to evolve into cell structure with an average diameter of about 0.7 μm. However, as shown in Fig. 6, the dislocation structure ahead of the crack tips has a vein structure or is loop patch under the condition of the overload. From the dislocation development in the low plastic strain amplitude, this is following by loop patch, vein, single-directional ladder-like wall of PSB, multiple-directional ladder-like wall of the PSB, wall and cell in the succeeding accumulation of plastic strain. Comparing cell to cell (with an average diameter of about 0.7 μm) dislocation evolution with vein to cell (with an average diameter of about 0.7 μm) dislocation evolution, it is obvious that the latter require much more time than the former. Therefore, based on the view of the microstructure, the front of the crack tip will distinctly retard the crack propagation when subject to a peak overload in the loading history. As the loading condition is returned to normal loading after overloading, the status of the retardation will be prolonged until the dislocation structure in front of the crack tips develops into a steady state similar to that seen in Fig. 3 (the dislocation structure under a steady state propagating rate); only then will the crack propagation rate return to the condition before overloading. With the variation of microstructure in front of the crack tip, the crack propagation subjected to a single peak overloading will retard the rate of crack propagation.

4.3. The microstructure at crack tip subject a single peak underloading

The specimen of crack propagation was subjected to a single peak underload (180 kg) after the propagation rate (about 3.0×10^{-7} mm per cycle) was stabilized. The rate of crack propagation is acceleration from 3.0×10^{-7} to 5.0×10^{-7} mm per cycle. The dislocation structure in

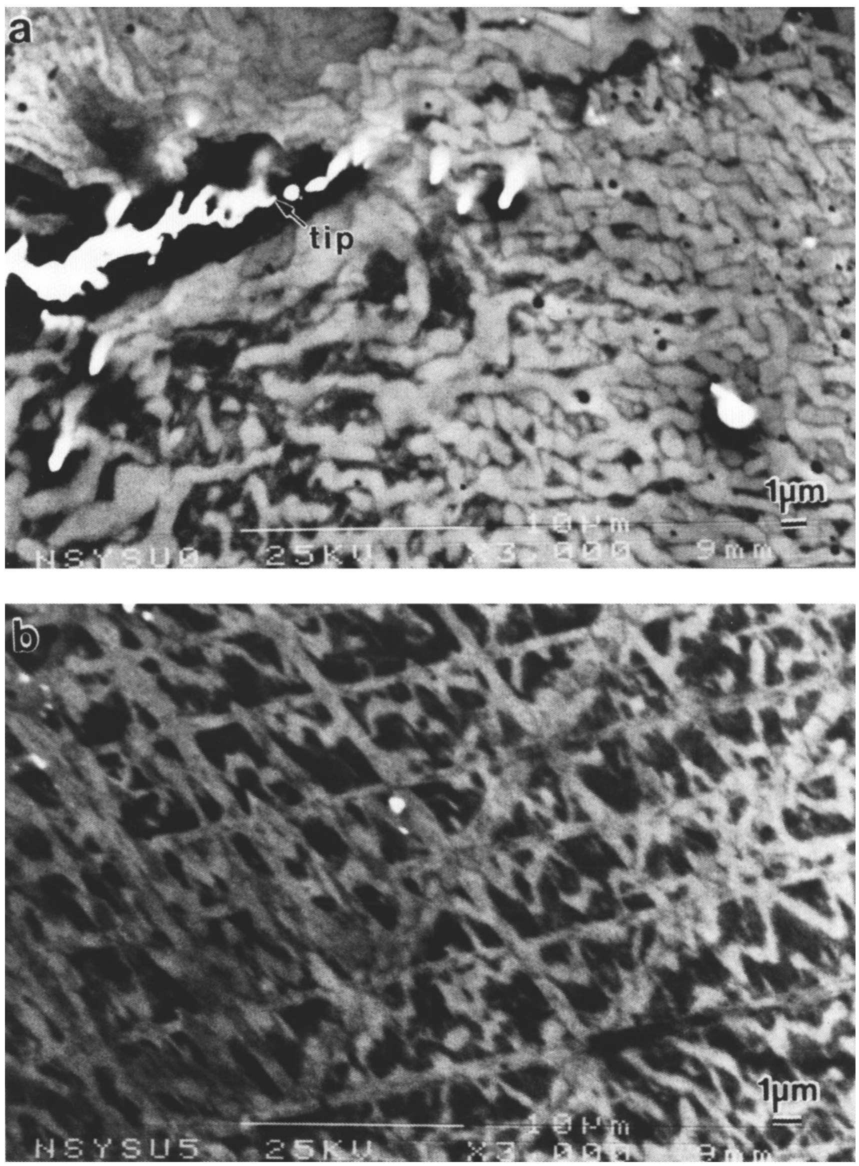

Fig. 10. The dislocation structure in front of the crack tip at a propagation rate of 10^{-7} mm per cycle under the condition of loading with double times of underloading. (a) Dislocation cell. (b) Checkerboard blocks are created by a multiple slip system.

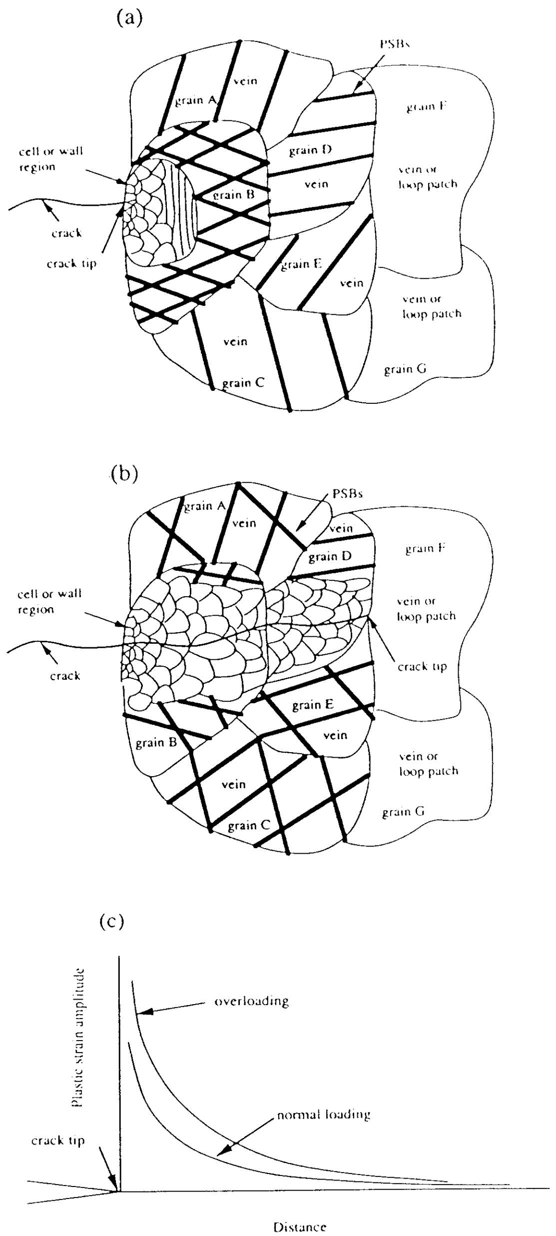

Fig. 11. The schematic the dislocation structures and plastic strain amplitude distribution in front of the crack tips. (a) Before overloading. (b) Overloading. (c) Amplitude of plastic strain.

front of the crack tips is shown in Figs. 9 and 10. We observed that the dislocation next to the crack tip is cellular in structure. Although the dislocation structure revealed in Fig. 9 (the case of underloading of one time of loading, i.e., compressing to about 180 kg and the crack propagation is acceleration to about 5.0×10^{-7} mm per cycle) is the same as the dislocation morphology in front of the crack tip with 10^{-7} mm per cycle propagation rate(Fig. 2), the size of the cellular region indicated in Fig. 9 is larger than that in Fig. 2. However, in Fig. 10 (condition of underloading of double times of loading, i.e., compressing to about 360 kg and the crack propagation is acceleration from 6.7×10^{-7} to 1.3×10^{-6} mm per cycle) the dislocation structure ahead of the crack tip is a column cell structure and is similar to the dislocation morphology in front of the crack tip with a 10^{-6} mm per cycle propagation rate (Fig. 1). According to literature reports, the rate of crack propagation is accelerated after the crack tip is subjected to a single peak underloading [20]. The result in Table 1, the crack propagation rate acceleration of the test point D (the rate of acceleration from 5.3×10^{-7} to 1.7×10^{-6} mm per cycle) is larger than point C (the rate of acceleration from 2.6×10^{-7} to 4.5×10^{-7} mm per cycle). This is because the underloading amplitude of point D (compressing 340 kg) is higher than at point C (compressing 170 kg), and the accumulation of plastic strain of point D is larger than of point C. Therefore, the

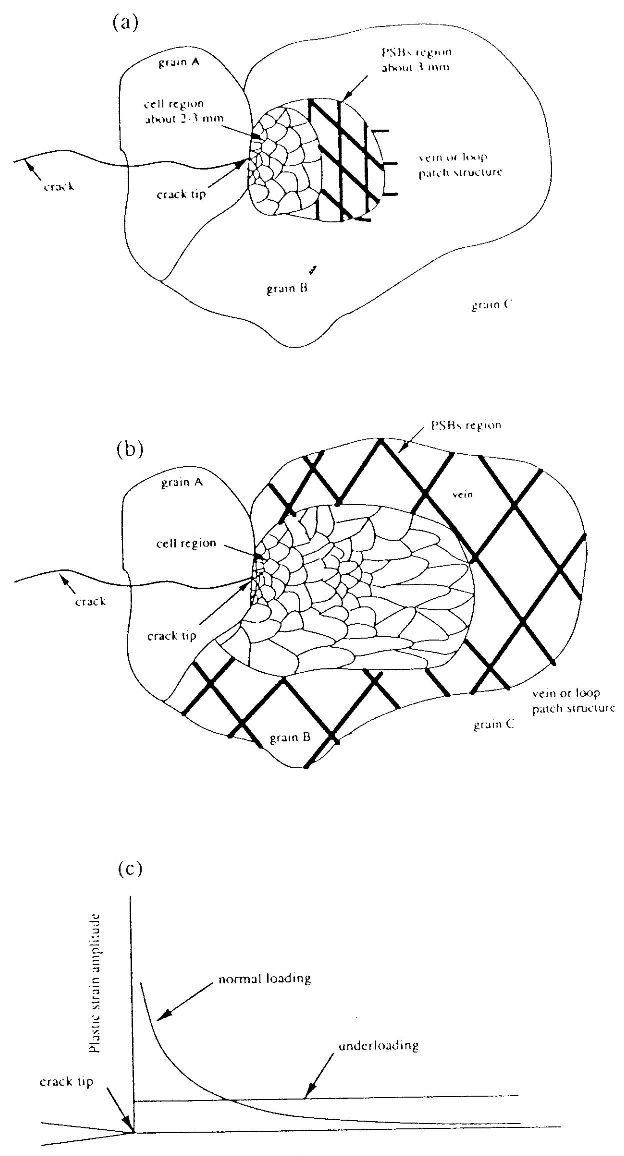

Fig. 12. The schematic the dislocation structures and plastic strain amplitude distribution in front of the crack tips. (a) Before underloading. (b) Underloading. (c) Amplitude of plastic strain.

dislocation in front of the crack tips evolution into cell structure, which is necessary for crack propagating at point D is faster than at point C. In order to demonstrate the phenomenon of acceleration of crack propagation after the crack tip was applied to a peak overloading, the schematic status of crack propagation and amplitude of plastic strain is shown in Fig. 12. During the process of the underloading, the crack tip was subjected to compressing stress. Thus, the crack tip was closed because the crack tip was unable to propagate (Fig. 12(a) and (b)). In the case of underloading, the strain concentration is smaller than the condition of overloading, and even can be neglected. This shows that the amplitude of plastic strain is equal everywhere in specimens in a condition of underloading (Fig. 12(c)). Therefore, the accumulation of plastic strain still increases and is equal everywhere in the specimen. However, the energy of plastic strain accumulation due to the process of underloading is stored in the form of dislocation structures. For example, the area of the cellular region is enlarged, as are regions of the other dislocation structures. The size of the vein or loop patch (Fig. 2) evolution into MPSBs (Fig. 9, in case of underloading of one time of loading) or even cell structure (Fig. 10(a), in case of underloading of double times of loading) is especially enlarged. The result of the dislocation morphology is indicated in Fig. 12(b). According to the above discussion, the crack propagation rate is determined by the rate at which dislocation structures close to the crack tips evolve into cell structures with an average diameter about 0.7 μm. At the same time, Fig. 3 shows that the range of dislocation structure located in front of the crack tips is vast and completely evolved, and thus the rate of crack propagation is faster (the rate of the crack propagation is 10^{-6} mm per cycle). Therefore, comparing the region of the dislocation morphology located ahead of the crack tips between Fig. 2 (10^{-7} mm per cycle propagation rate) and Figs. 9 and 10 (under a condition of underloading), the latter has a much wider area and more full evolution than the former. Thus, the crack propagation rate of the latter is faster than that of the former. As the condition of loading is returned to normal loading after underloading, the status of the acceleration of the crack propagation will regress until the dislocation structures close to the crack tips are reduced into the same as seen in Fig. 2 (the dislocation structure under a 10^{-7} mm per cycle steady state propagating rate), and then the crack propagation rate will return back to the condition of original load. Based on the change of the microstructure at the crack tip, the crack propagation subjected to a single peak underloading will increase the rate of crack propagation.

5. Conclusions

(1) For pure copper, there are condition which will cause the retardation or acceleration of the crack propagation after the crack tip is subjected to a peak of overload or underload in the steady state of loading.

(2) Under a steady state, when the crack propagation rate is subjected to a single peak overloading, in which the microstructure in front of the crack tips is passed through from cell structure into vein structure, the rate of crack propagation will be retarded.

(3) Under a steady state, when the crack propagation rate is subjected to a peak underloading, the region of dislocation structure in front of the crack tips is enlarged and more fully evolved than the dislocation structure before underloading. Hence, the crack propagation rate will be accelerated.

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