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Tensile orientation dependence of surface-roughness evolution in cyclically deformed Fe–30%Cr alloy single crystals

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Abstract

In order to investigate orientation dependence of surface roughness evolution, cyclic deformation tests have been carried out in Fe–30%Cr alloy single crystals having the tensile axes of [233], [122], [011] and [001]. Formation of persistent slip bands (PSBs) characterized by the surface roughness was observed in all the orientations. Atomic force microscope (AFM) observations revealed that the maximum heights of the PSB extrusions in the single-slip-oriented specimens ([233] and [122]) were larger than those of the [011] and [001] specimens by a factor of 7.5 and 15, respectively.

Keywords: Cyclic deformation; Ferritic stainless steel; Single crystal; Extrusion; PSB

1. Introduction

It is well known that the surface topography due to persistent slip band (PSB) formation plays an important role on the nucleation of fatigue cracks as has been revealed by pioneering works in copper [1,2]. The PSB can accommodate large plastic strain and subsequently gives rise to pronounced surface roughness. The surface roughness results from both extrusion of PSB volume and fluctuation of PSB surface.

The PSB formations have been recognized also in the ferritic stainless steel single crystals having a b.c.c. structure [3–5]. It is likely that the tensile orientation also affects the PSB topography and subsequent crack initiation process. However, no systematic studies have been performed on the orientation dependence of the surface roughness and the following fatigue crack nucleation at the PSB in b.c.c. metals and alloys.

In the present study, fatigue tests under constant plastic strain amplitudes were carried out in the Fe–30%Cr alloy single crystals having various tensile axes which give rise to single-, double-, and multiple-slip. Attention was paid to the relationship between the surface roughness and cyclic stress–strain response. We attempted to understand the orientation dependence of the surface evolution by a proposed extrusion model [6]. The extrusion model was compared with the internal dislocation activity deduced from the asymmetric stress amplitude which was often observed in the fatigued b.c.c. metals [7–10].

2. Experimental procedure

The single-slip-oriented (the [233] and [122] tensile axes), the double-slip-oriented (the [011] tensile axis) and the multiple-slip-oriented specimens (the [001] tensile axis) with a gauge length of 4 mm and a cross section of 2×2 mm^2 were cut by spark erosion from Fe–30%Cr alloy single crystals grown by the Bridgman method. All the maximum-resolved-shear-stressed (m.r.s.s.) planes are {112}.

Cyclic deformation tests were carried out in air at room temperature in a servo-hydraulic machine. A plastic strain amplitude was set at 8×10^{-4}. Frequency of the cyclic deformation was controlled such that a total strain rate was kept to be 1×10^{-3} s^{-1}.

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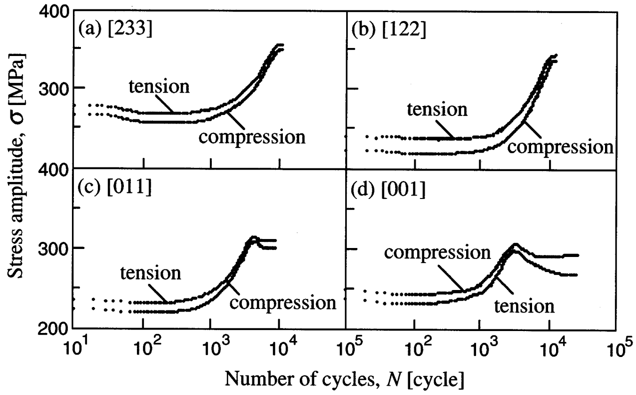

Fig. 1. Changes in the stress amplitudes of both tensile and compressive portions during cyclic deformation tests under a constant plastic strain amplitude of 8×10^{-4}.

Table 1
Stress asymmetry measured at the end of experiment[a]

Tensile axis	Stress asymmetry
[233]	0.015
[122]	0.013
[011]	0.030
[001]	−0.090

[a] The stress asymmetry is defined as the difference in the stress amplitude between tensile and compressive regions, which are normalized by an average value of them.

3. Results

3.1. Cyclic hardening and stress asymmetry

Fig. 1 shows cyclic hardening curves of the tensile and compressive stress amplitudes. The [233] and [122] specimens continued to harden. On the other hand, cyclic softening was observed in the [011] and [001] specimens. Maximum values of the stress amplitude were of 350 and 310 MPa for the single-slip (the [233] and [122] tensile axes), the double and multiple-slip (the [011] and [001] tensile axes) orientations, respectively.

The stress amplitudes were different between tensile and compressive regions in respective specimens as seen in Fig. 1. In order to evaluate the difference, we calculated the 'stress asymmetry'. The value of the stress asymmetry was defined as the difference in stress amplitude between tensile and compressive regions, which was normalized by an average stress amplitude of them. The stress asymmetry measured at the end of experiment is shown in Table 1. Since the stress amplitudes of tensile region were higher than those of compressive region, the values of the stress asymmetry were positive, except for the [001] specimen at which the compressive stress amplitude was high on the contrary. It is noted that the absolute value of the stress asymmetry in the [001] specimen was higher than those of the [233] and [122] ones by a factor of six, whereas there was no significant difference in the average stress amplitude.

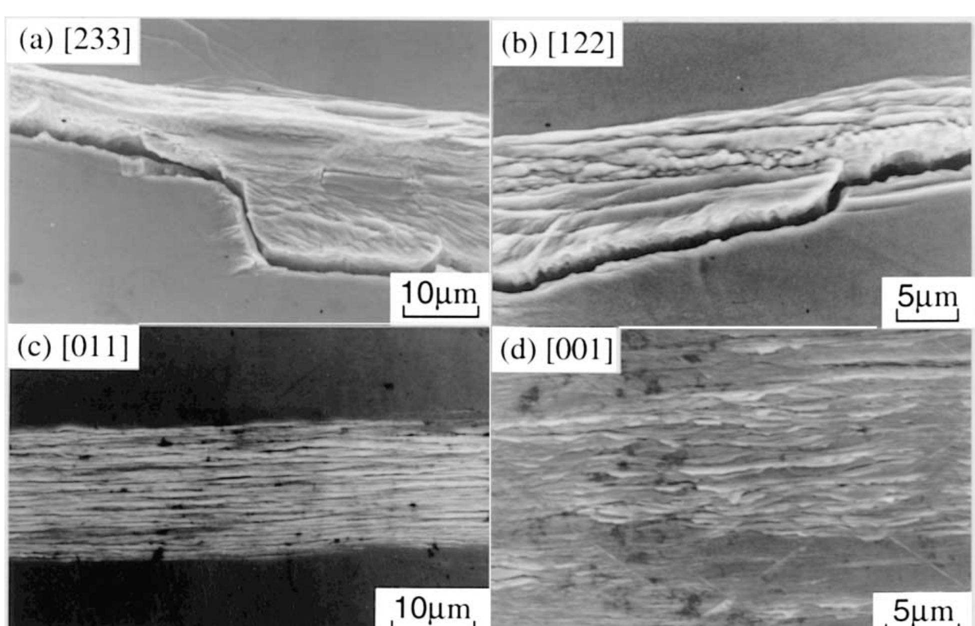

Fig. 2. SEM photographs showing the PSBs which were developed along the {112} m.r.s.s. planes. It is noticeable that the fatigue crack was nucleated at the PSB–matrix interface in the [233] and [122] specimens.

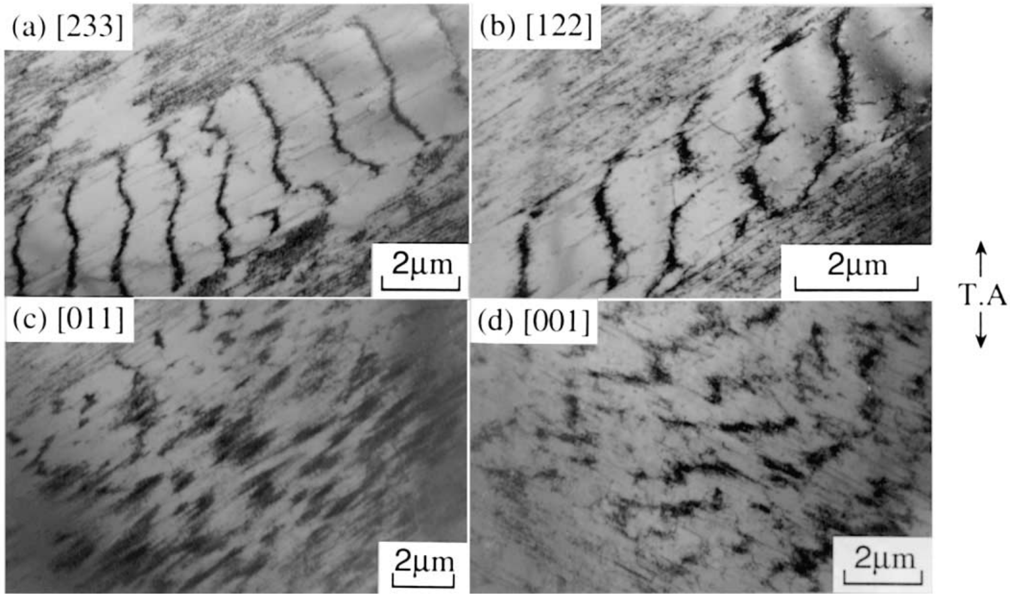

Fig. 3. TEM observation of the dislocation arrangement in the PSBs. Plane of thin foils is parallel to the {110} side surface.

3.2. Persistent slip bands

Development of PSBs revealing surface roughness was recognized by SEM observation, as shown in Fig. 2. The corresponding planes of these PSBs parallel to the side-surface normal were {112} primary slip planes. In addition to these PSBs, indistinct slip bands inclined to the tensile direction were locally found by optical microscope observation of the top surface on the [001] specimen. This slip trace in the [001] specimen corresponds to the slip activity at which the slip vector has little top-surface component. Hence, it is probable that the plastic deformation in the multiple-slip-oriented specimen was accommodated by the simultaneous operations of individual PSBs which were formed along different {112} planes. The fatigue cracks were nucleated at the PSB–matrix interface in the [233] and [122] specimens, as seen in Fig. 2. On the other hand, no fatigue cracks were observed in the [011] and [001] specimens until at least 10 000 and 30 000 cycles, respectively.

Fig. 3 shows TEM observation of dislocation structure in the PSBs. These PSBs were composed from the dislocation walls and channels. This structure is analogous to that of the PSB observed in the copper single crystals. The substructures of the PSBs were somewhat different among the tensile axes. In the [233] and [122] specimens, the dislocation walls were arranged at a regular spacing. On the other hand, the dislocation walls of distorted shape were distributed irregularly in the [011] and [001] specimens. It was also noted that the Burgers vector of the dislocations was one kind in the PSBs of the [011] and [001] specimens although the dislocations contained in the surrounding matrices had some kinds of Burgers vectors. This observation is compatible with the mentioned deformation model of the multiple-slip-oriented specimen.

Surface topography of the PSB was measured using an atomic force microscope (AFM). The profiles of the PSBs are represented in Fig. 4. The maximum heights of the PSB extrusions were presented in Table 2, together with the responsible slip directions. All the slip vectors, which are related to the PSB formation at the surface, had no side-surface component. Although there is no significant difference in top-surface component of the normalized slip vector, the surface roughness de-

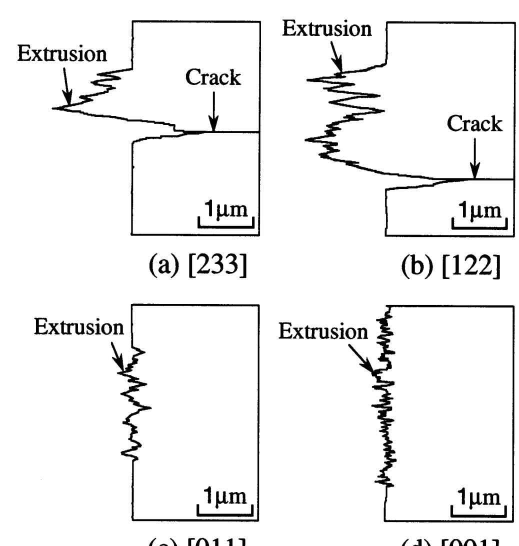

Fig. 4. AFM observation of surface profile at the PSB. In addition to the extrusions, the profile of the fatigue crack nucleated along the PSB–matrix interface was also seen in the [233] and [122] specimens.

Table 2
The maximum heights of the PSB extrusion and the related slip directions[a]

Tensile axis	Maximum height of extrusions (nm)	Primary slip direction	Components of the normalized slip direction transformed into specimen coordinate		
			x (Top surface)	y (Side surface)	z (Tensile axis)
[233]	1500	$[1\bar{1}\bar{1}]$	0.870	0.000	−0.492
[122]	1500	$[1\bar{1}\bar{1}]$	0.816	0.000	−0.577
[011]	200	[111]	0.577	0.000	0.816
		$[1\bar{1}\bar{1}]$	0.577	0.000	−0.816
[001]	100	[111]	0.816	0.000	0.577
		$[11\bar{1}]$	0.816	0.000	−0.577

[a] The normalized slip vectors transformed into the specimen coordinate are also listed. The $[1\bar{1}1]$ and $[1\bar{1}\bar{1}]$ slip directions are omitted in the [001] tensile axis because they have no top surface component.

pended strongly on the tensile orientation. The PSB extrusions of the single-slip-oriented specimens ([233] and [122]) were evolved to be the maximum heights of 1500 nm at the end of experiments. On the other hand, the maximum heights of the [011] and [011] specimens were 200 and 100 nm, the maximum heights of the single-slip-oriented specimens were higher than those of the [011] and [001] specimens by a factor of 7.5 and 15, respectively. It is apparent that the volume expansions of the PSB in the [233] and [122] specimens primarily cause such a difference in the maximum height.

4. Discussion

In the present study, the PSB extrusions of this kind were pronounced in the [233] and [122] specimens rather than in the [001] and [011] specimens as seen in Fig. 4. Here, we turn our attention into the difference in cyclic response between these specimens. It is noticeable that the absolute values of the stress asymmetry in the [233] and [122] specimens were substantially smaller than those of the double and multiple-slip-specimens.

The existence of such a stress asymmetry in the b.c.c. crystals has been interpreted by asymmetric behavior of screw dislocations sheared to 'twinning' and 'anti-twinning' directions along {112} plane [11,12], the flow shear stress of the screw dislocation becomes high under the anti-twinning shearing compared with the twinning shearing. The PSBs in the present specimens were arranged parallel to such {112} planes. The above-mentioned asymmetry rule of the flow shear stress along the {112} plane is consistent with the present results that the tensile stress amplitude was large in the [233], [122] and [011] specimens and was small in the [001] specimen. It can be said that the magnitude of the stress asymmetry reflects the screw dislocation movement along the {112} plane [5,13]. Accordingly, relative contribution of the screw dislocation motion is probably higher in the [001] and [011] specimens than in the [233] and [122] specimens especially at the PSBs which can accommodate large plastic strain. On the contrary, one can expect that the [233] and [122] specimens are deformed under the high contribution of edge dislocation movements.

Essmann et al. [6,14] have proposed a mechanism which accounted for the extruded volume of PSB by incorporating the production of a large amount of vacancies. This extrusion model presumes the mutual annihilation of the vacancy-type dipole of the edge dislocations which glide along parallel slip planes less than a critical distance apart. The preferential annihilation of the vacancy dipole is based on the estimation that formation energy of vacancies is considerably lower than that of interstitials. Accordingly, for the [233] and [122] specimens showing the highly evolved extrusion, the expected high activity of the edge dislocations is consistent with the vacancy production model based on the edge dislocation annihilation.

The extrusion model of the vacancy production also predicted fatigue crack nucleation along an interface between the PSB and matrix [6]. This is because the expansion of the PSB volume induces an additional shear stress along the interface in the vicinity of free surface. This mechanism agrees with the experimental observation that the fatigue cracks were preferentially nucleated along the interfaces in the single-slip-oriented specimens.

It is also noted that a lot of closely-spaced hills and valleys were recognized by the AFM observation on the surface profile especially in the [001] specimen, although the volume expansion was almost negligible. This kind of the surface roughness should be connected closely with irreversible slip process. The surface roughness at the PSB has separately been explained by considering the fluctuation of a random distribution of the irreversible slip line segments [15], aside from the volume expansion of the PSB. This model assumed that the irreversible slip occurred as a result of the mutual annihilation of the screw dislocations by cross slip.

According to this model, it is inferred that the movements of the screw dislocations give rise to the surface fluctuation without the production of vacancies. Hence, in the [001] specimen, the high stress asymmetry induced by the screw dislocation motion is in agreement with both the frequent occurrence of the irreversible slip and the absence of the extruded volume at the PSB as seen in Fig. 4.

Because the PSB dislocation structures were certainly different among the tensile orientation as seen in Fig. 3, local process of plastic deformation in the PSB should vary also with the tensile orientation. This variation of the plastic deformation mechanism probably attributes to the difference in the stress asymmetry. However, details of the mechanism that can explain the difference in the stress asymmetry among the tensile axes are still unknown.

5. Conclusions

PSBs along {112} planes were formed at the cyclically-deformed Fe–30%Cr single crystals having the [233], [122], [011] and [001] tensile orientations at the constant plastic strain amplitude of 8×10^{-4}. The evolutions of surface roughness were recognized at the PSBs by the AFM observation.

The extent of the surface roughness depended strongly on the tensile axis. The maximum heights in the single-slip-oriented specimens were larger than those of the [011] and [001] specimens by a factor of 7.5 and 15, respectively.

The orientation dependence of the surface roughness could be understood from the extrusion formation model proposed by Essmann et al., by incorporating the dislocation activity which is deduced from the asymmetric stress amplitude observed in the present experiments.

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References

[1] Z.S. Basinski, S.J. Basinski, Scr. Metall. 18 (1984) 851.
[2] A. Hunsche, P. Neumann, Acta Metall. 34 (1986) 207.
[3] B. Šesták, Z. Vicherková, V. Novák, S. Libovicky, J. Brádler, Phys. State Solid (a) 104 (1987) 79.
[4] B. Šesták, V. Novák, S. Libovicky, Phil. Mag. A 57 (1988) 353.
[5] Y. Kaneko, T. Mimaki, S. Hashimoto, Acta Mater. 47 (1999) 165.
[6] U. Essmann, U. Gösele, H. Mughrabi, Phil. Mag. A 44 (1981) 405.
[7] H. Mughrabi, C. Wüthrich, Phil. Mag. 33 (1976) 963.
[8] T. Magnin, J.H. Driver, Mater. Sci. Eng. 39 (1979) 175.
[9] M. Anglada, B. Etemad, J.A. Planell, F. Guiu, Scr. Metall. 14 (1980) 1319.
[10] M. Anglada, F. Guiu, Phil. Mag. A 44 (1981) 499.
[11] S. Takeuchi, E. Furubayashi, T. Taoka, Acta Metall. 15 (1967) 1179.
[12] V. Vitek, Proc. R. Soc. London A 352 (1976) 109.
[13] Y. Kaneko, T. Mimaki, S. Hashimoto, Mater. Sci. Eng. A245 (1998) 233.
[14] U. Essmann, Phil. Mag. A 45 (1982) 171.
[15] K. Differt, U. Essmann, H. Mughrabi, Phil. Mag. A 54 (1986) 237.