Cyclic Deformation of Hastelloy and Inconel Alloys and Slip Bands Formation

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Abstract: *Hastelloy C22 and Inconel 600 and 601 alloys specimens were cyclically deformed. Specimens were sectioned and investigated. Results indicated that the grain structure of Hastelloy C22 revealed planar slip bands, whereas Inconel 600 and 601 showed slip bands having triangular ribbon morphology. The triangular ribbon bands were more distinct in Inconel 601 than in Inconel 600.*

Keywords: *Hastelloy, Inconel, planar bands, triangular ribbon bands, cyclic deformation.*

I. Introduction

Slip bands are very common features in fatigued alloys such as aluminum alloy and nickel alloys [1,2], the formation of which has been attributed to their low stacking-fault energy (SFE). Low SFE leads to the formation of wide and extended dislocations, with reduced ability of screw dislocations to cross-slip onto other slip planes.

The occurrence of slip bands in materials depends on their stacking-fault energy. However, several authors [3–5] have demonstrated that reduced stacking-fault energy may not be the reason for the manifestation of deformation as slip banding in some solid solutions. They suggested that carbon content plays a great role in determining the nature of bands in nickel alloys [3-5] and other precipitation hardened alloys. The precipitates within the matrix sheared due to dislocations movement [5-8]. Normally, precipitation-hardened alloys show wavy bands in a way similar to that exhibited by single-phase alloys with high stacking-fault energy. Clavel and Pineau suggested that that the formation of slip bands was the prime factor for initiating nucleation which leads to fracture in nickel-based alloys. They also studied cyclic deformation of supper alloy IN718 concluded that the precipitates were slipped during cyclic deformation. Worthem [9] also observed a set of groups of deformation slip bands during cyclic deformation of IN718. Therefore, although slip bands have been observed due to SFE by several investigators [6–8], there seems to be no study on the investigated the effect of carbon content on slip bands of Hastelloy C22, Inconel 600, and Inconel 601. In the present study, scanning electron microscope (SEM) was employed to investigate the morphology of slip bands formed in these alloys during cyclic deformation.

II. Materials And Experimental Procedures

To investigate the morphology of slip bands in Ni-based alloys, round bars of Hastelloy C22, Inconel 600 and Inconel 601 were machined into standard fatigue specimens. Their chemical compositions are given in Table 1. Prior to tension-tension fatigue testing, the machined samples were subjected to heat treatment at 1000ºC for 1 hour followed by air cooling to ensure an equiaxed microstructure and therefore reproducible mechanical properties. Fatigue testing was conducted at room temperature under the same test parameter using INSTRON1332 testing machine which was connected to INSTRON8500 programmable control unit with a frequency of 10 Hz. All tests were conducted at room temperature. After fatigue failure, discs were cut from regions immediately adjacent to the fracture surface and perpendicular to the loading axis using an electrical discharge machine (EDM). They were subsequently polished to high smoothness and etched using modified Kalling’s II reagent.

Table 1: Chemical compositions of three Ni-based alloys (wt.%).

Alloy	Ni	Cr	Fe	Mo	C
Hastelloy C22	Bal.	21.42	2.95	13.67	0.003
Inconel 600	Bal.	15.77	8.58	-	0.05
Imconel 601	Bal.	22.14	16.09	-	0.3

III. Results

The morphologies of the slip bands formed in the cyclically deformed specimens of the Hastelloy C22, Inconel 600 and Inconel 601 alloys are shown in "Fig. 1", "Fig. 2", and "Fig. 3", respectively. Slip bands was observed on the surfaces of all specimens tested, but the appearance of slip bands in the specimens of the three alloy specimens was different with respect to slip band density. The activation of multiple planar bands in Hastelloy C22 is shown in "Fig.1", where the slip bands formed in two directions within the grain. This suggests that cyclical deformation of Hastelloy C22 with straight grain boundary structure exhibited slip bands similar to those found in materials with low stacking fault energy. Two groups of parallel slip bands, with one group inclined at approximately 70° to the other, were found is the deformed alloy. This suggests that Hastelloy C22 experienced higher plastic deformation and longer fatigue life as compared to Inconel 600 and Inconel 601.

The morphology of slip bands formed in Inconel 600 and Inconel 601, as shown in "Fig. 2" and "Fig.3", is different from that of C22. The bands formed in these materials are in the form of triangular ribbons within the grain. The bands morphology may therefore be dependent on their carbon contents is responsible for the type of carbides morphology as shown on Table 1.

Although slip bands are generally straight and continuous, some interruptions, kinks and divergences in slip bands may be readily visible at high magnifications as shown in "Fig.1".

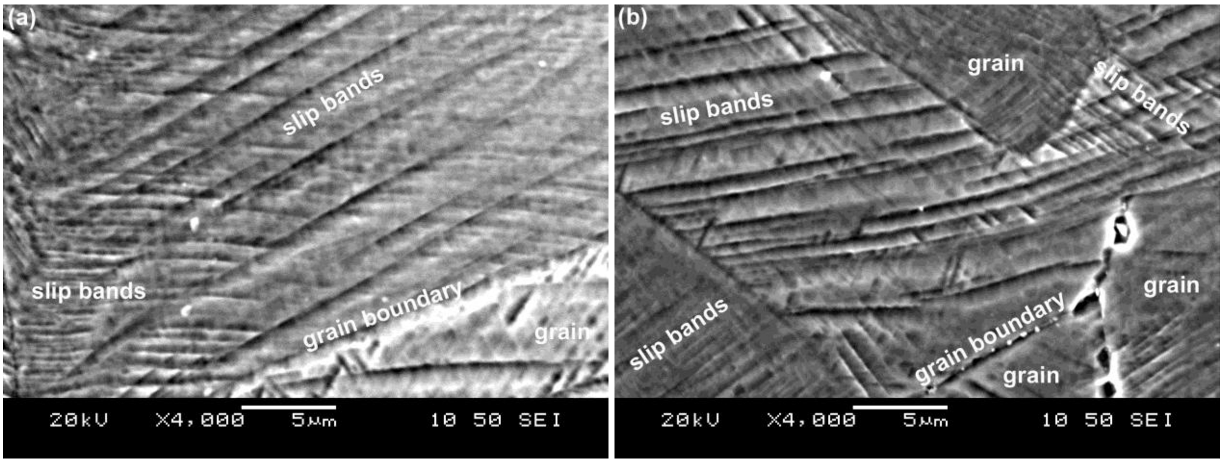

Figure 1: Scanning electron micrograps of Hastelloy C22 specimens showing planar bands fatigued at (a) 500 MPa and $7x10^6$ cycles, (b) 550MPa and $3x10^6$ cycles.

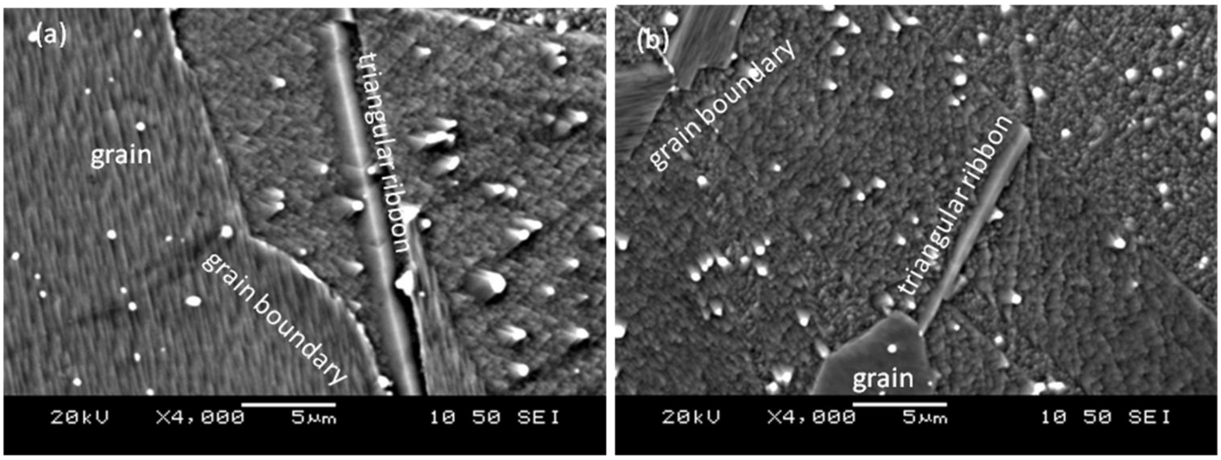

Figure 2: Scanning electron micrographs of Inconel 600 specimens showing short triangular ribbon-type slip bands fatigued at (a) 500MPa and $7x10^5$ cycles, (b) 550MPa and $3x10^5$cycles.

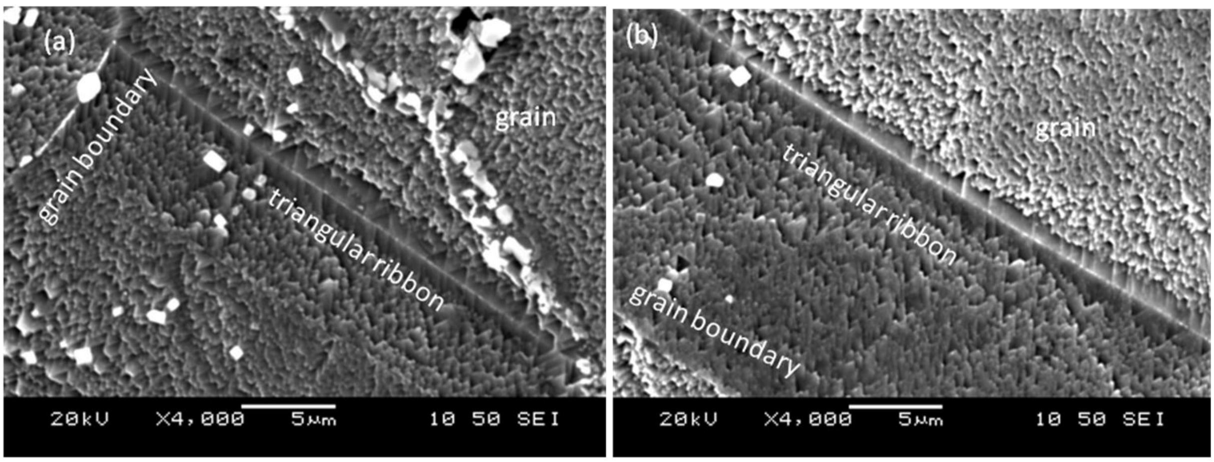

Figure 3: Scanning electron micrographs of Inconel 601 specimens showing long triangular ribbon bands fatigued at (a) 500MPa, and $430x10^3$ cycles, (b) 550MPa and $3x10^5$cycles.

IV. DISCUSSION

It is well accepted that slip bands produced by cyclic deformation can manifest as orientated distribution of defects such as dislocations. These defects would affect the deformation behavior of the grain structure greatly, causing deformation to take place readily along the slip planes. A strong evidence for the occurrence of slip nucleated in grain boundaries was shown in copper by Vinogradov [10]. Therefore, it is reasonable to suggest that the formation of slip bands in the three Ni-based alloys tested in the present study resulted from the grain boundary as shown in "Fig. 1", "Fig. 2", and "Fig. 3".

In the case of a complete stress-strain cycle slip bands may disappear totally leaving few slip bands in the specimen surface. However, some micro structural changes do take place internally owing to plastic incompatibility, especially at triple junctions and grain boundaries, resulting in the formation of void-type defects along the slip plane and grain boundary. With further cycling, the concentration of this type of defects would increase gradually. It is also likely that coalescence of defects and formation of voids would occur due to further plastic deformation. At the same time micro cracks would appear at the surface because fatigue damage usually occurs more easily on surfaces. Further cycling would not only promote void formation, but it will increase the level of plastic deformation; when the plastic deformation reaches a threshold value, the material cracks and eventually fractures. This would result in the formation of deformation steps during cyclic deformation resulting in a net displacement in the surface after cyclic deformation this was more pronounced in alloy C22 as shown in "Fig.1".

Accumulation of cyclic plastic deformation would eventually bring about the formation of slip bands as shown in "Fig.1", "Fig. 2" and "Fig. 3". It is shown clearly in the present paper that there is a direct connection between morphology of slip bands and morphology of grain boundary, which, dependent on the amount of carbides formed on grain boundary. It can be seen that the higher the carbon content of the alloy, the greater is the chance to nucleate triangular ribbon-type slip bands at the grain boundary. However, the slip bands morphology factors responsible for cyclic deformation are still open questions and need further investigations.

V. CONCLUSION

The current study briefly investigated the morphologies of slip bands in Hastelloy, and in Inconel alloys cyclically deformed. Results, revealed that planar type slip bands in Hastelloy C22, whereas triangular ribbon type slip bands in Inconel 600 and Inconel 601 alloys. The triangular ribbon bands were more distinct in Inconel 601 than in Inconel 600. The formation and morphology of the two types of slip bands may be attributed to the carbon content of the alloys.

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