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Twin-dislocation and twin–twin interactions during cyclic deformation of a nickel-base single crystal TMS-82 superalloy

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ABSTRACT

The characteristics of twin-dislocation and twin–twin interactions in a nickel-base single crystal TMS-82 superalloy have been investigated after thermomechanical fatigue (TMF) testing. The resistance for a growing twin increases significantly with the introduction of tangled dislocations. When there are few dislocations at the primary stage of TMF cycling, twinning dislocations can move straight or pass through a pre-existing twin smoothly. When there exist large amounts of dislocations during TMF process, a propagating twin will be hindered in varying degrees. Dislocations will not affect the morphology of a pre-existing twin.

1. Introduction

Superalloys, which are regarded as high-temperature materials, are used in the components for gas turbine engines and heat exchangers. They display unique resistance to mechanical and chemical degradation over extended periods of time at elevated temperatures [1–3]. However the lifetime of these superalloys is strongly dependent upon and limited by their microstructural characteristics [1,4]. The microstructure of a typical nickel-base superalloy consists of γ channel (the fcc structure) and γ' precipitates (the $L1_2$ structure). Defects such as vacancies, dislocations, stacking faults and twins can occur in this γ/γ' structure when subjected to tensile and compressive tests, which strongly influence the mechanical properties of the superalloys [5,6]. As one of these defects, deformation twins play a pivotal role in the strength and ductility of the superalloy. In a γ' strengthened Fe-based superalloy, deformation twins occur at intermediate temperature, leading to an improvement of strength and ductility, but abundance of twins at high temperature lead to a degradation of strength and ductility [7]. The relevant microstructural interactive effects refer to the relationship between dislocations and twin boundaries.

The twin-dislocation and twin–twin interactions in fcc structure were investigated and the conclusions were made as follows: (1) twin–twin interactions are accomplished by secondary twinning at the intersection [8], (2) dislocations can propagate across the existing twin boundaries under appropriate geometrical conditions [8] or dissociate in order to relax stress concentration [9]. Recently twin intersections were studied by transmission electron microscopy (TEM) observation, and their configurations depended strongly on temperature and applied stress [10,11]. A geometrical restrictive condition for a deformation twin to pass through another one and form a secondary twin at the intersection was put forward [12]. Generally speaking, different opinions were mentioned about twin-dislocation and twin–twin interactions in fcc structure.

Most of the previous work on the twin-dislocation and twin–twin interactions has been focused on the common fcc structure [10–13]. In nickel-base superalloys, most researches have involved in the mechanism of twinning nucleation, ignoring the process of twin propagation [14–17]. In this work, growth characteristics of twins in a TMS-82 superalloy during thermomechanical fatigue (TMF) cycling are investigated with the aid of TEM observations. The evolution of twin-dislocation and twin–twin interactions at different stages of TMF cycling is discussed.

2. Experimental

A nickel-base single crystal TMS-82 superalloy was chosen for this work. The nominal composition of this alloy in weight percent is given in Table 1. The alloy was solution heat treated both at 1300 °C for 1 h and 1320 °C for 5 h followed by a two-stage aging

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Table 1
Compositions of TMS-82 superalloy in wt.%.

	Ni	W	Al	Ti	Ta	Co	Cr	Mo	Hf	Re
TMS-82	62.4	8.7	5.3	0.5	6.0	7.8	4.9	1.9	0.1	2.4

process at 1150 °C for 4 h and 870 °C for 20 h. The volume fraction of a the γ' phase is about 60% and the average size of the γ' cuboids is 0.4 μm. The specimens were machined from cast bars with their longitudinal axis paralleling to the [0 0 1] direction. Cylindrical specimens for TMF tests with a gauge length of 135 mm and a diameter of 6 mm were prepared by mechanical machining and grinding.

TMF tests were carried out on a MTS 810 servo-hydraulic TMF machine with a capacity of ±50 kN. To simulate the actual conditions of blades and vanes, the following experimental conditions were chosen (Fig. 1(a) and (b)): temperature range, 400 °C ⇔ 900 °C in air; total strain range, ε_t = 1.28% (±0.64%); frequency, $(0.1 + t_h)$ (h)/cycle, where t_h = 1 h was the hold time at the maximum testing temperature (900 °C); wave form, trapezoidal; phase, out-of-phase. During the hold time of 1 h at the maximum compression strain, there was a stress relaxation process. Then the TMF test gradually proceeded from compression to tension. A tensile plastic deformation was present around 400 °C on the top of the curve (Fig. 1(c)).

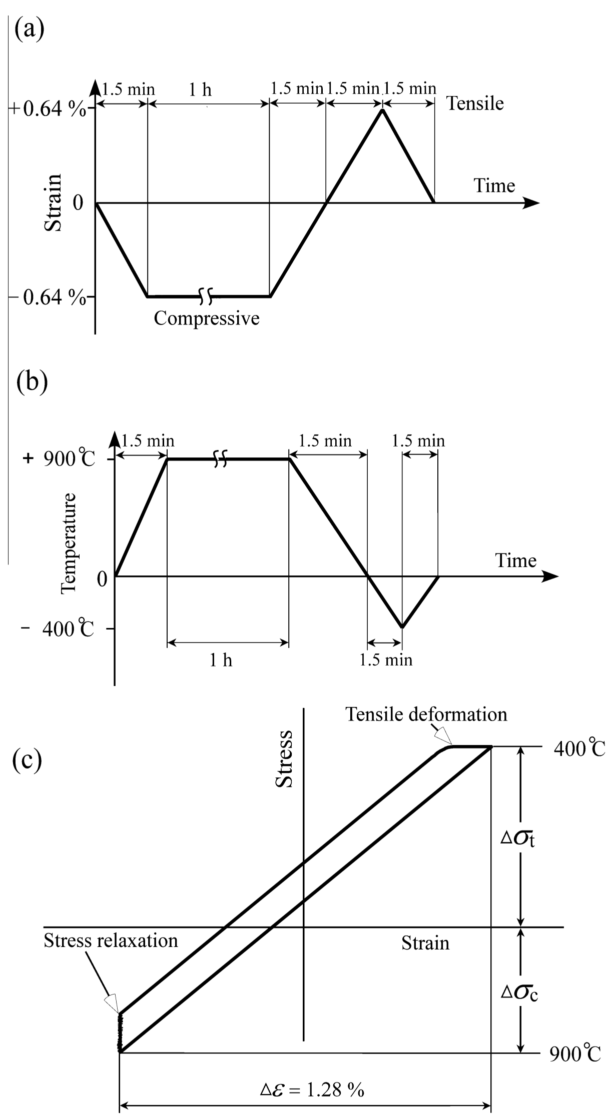

Fig. 1. (a) Illustration of TMF test and (b) Schematic drawing of hysteresis loop.

The microstructures of all fatigue-tested specimens were obtained with the aid of a JEOL 2000 FX II transmission electron microscope (TEM). Foils for TEM observation were obtained by cutting 0.3 mm thick discs perpendicular to the tensile axis of the TMF-tested specimens using a low speed diamond saw. They were mechanically thinned to 40–50 μm and then electropolished using a solution of 10% perchloric acid in methanol at −20 °C. All TEM micrographs were imaged under two-beam conditions: dark field and bright field. After TMF failure, the observation for the deformed microstructures was carried out by using a JEOL JSM-6060 scanning electron microscope (SEM).

3. Results and discussion

3.1. Twin-dislocation interactions

Fig. 2 shows the microstructure of an interrupted specimen after the second stress relaxation of the TMF cycling. One can see that the γ' precipitates are embedded in the γ phase uniformly and there are rare dislocations in the γ/γ' structure of TMS-82 superalloy. Thin and straight twin plates, which originated from γ/γ' interfaces as demonstrated in Fig. 2(a), propagate homogeneously through γ channel and γ' precipitates without any disturbance or interruption. In this case, the true thickness of twins

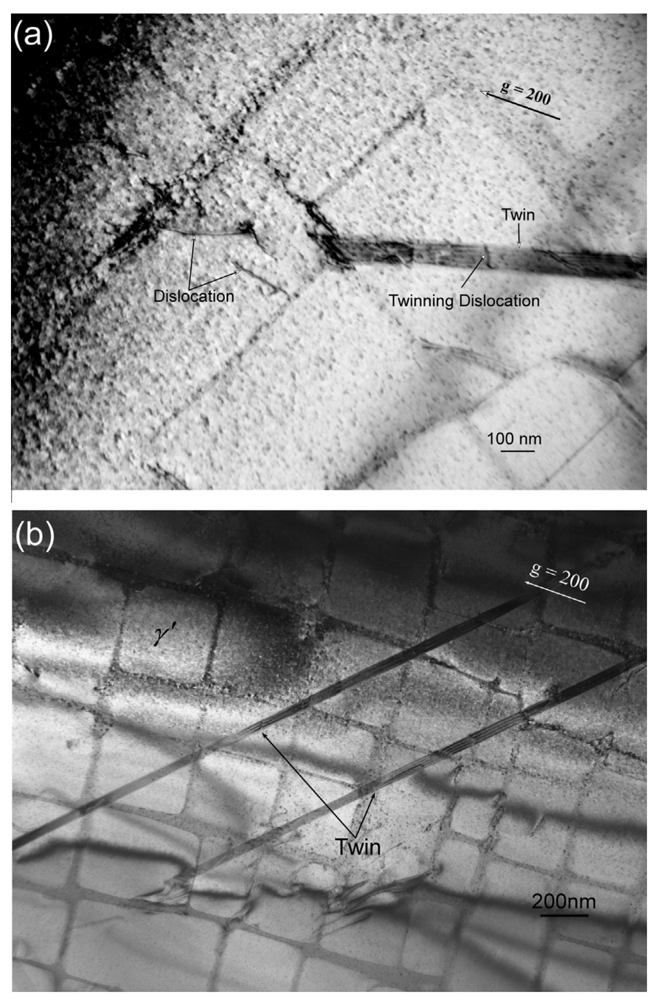

Fig. 2. Microstructure of superalloy TMS-82 interrupted after the second stress relaxation showing configuration of twins. Beam direction (BD) ~ [0 0 1].