NEW METHODS OF DAMAGE AND FAILURE ANALYSIS OF STRUCTURAL PARTS
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EVALUATION OF HETEROGENEOUS SLIP DEFORMATION BY TAYLOR ANALYSIS

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ABSTRACT: The tensile stress field in deformed α-titanium was easily introduced along <0001>. The stress may assist to open the crack on {0001}. In the saturated dislocation structure, piled-up dislocations develop not only stress concentration at the grain boundary but also lattices rotation in the neighbor of boundary. Since the stress concentration is larger than the coordinating stress by lattice rotation, the stress concentration by piled-up dislocations may strongly affect to open the initiating crack. Piled-up dislocations on {111} in a soft grain of FCC polycrystalline induced strain incompatibility with neighbor grain, and the stress was geometrically generated along <111> in the hard grain. The result agreed to the subsurface crack initiation in high-nitrogen austenitic steel.

KEY WORDS: Taylor analysis, polycrystalline, critical resolved shear stress, strain incompatibility, tensile yielding

テイラー解析による不均一すべり変形の評価

概要： αチタンでは、<0001>方向に引張応力が生じ易く、{0001}き裂を開口する応力成分と考えられる。転位列組織では、堆積転位にともなう応力集中と、外部応力の変形拘束にしたがった回転にともなう応力が存在する。前者の方が大きいことから、き裂開口に必要な引張応力は転位堆積の影響が支配的である。FCC 多結晶中に形成した堆積転位による応力場の影響を隣接結晶粒との方位関係から解析し、<111>方向に引張応力が生じることから、高窒素鋼のファセット割れを支持するものである。

HODNOCENÍ HETEROGENNÍ SKLUZOVÉ DEFORMACE POMOCÍ TAYLOROVY ANALÝZY

ABSTRAKT: V deformovaném α-titanu vzniká snadno tahové napěťové pole podél krystalografického směru <0001>. Toto napětí může přispět k otevření trhliny na rovinách {0001}. V saturované dislokační struktuře vytváří nakupení dislokací nejen koncentraci napětí na hranici zrna, ale také mřížkovou rotaci v sousedství hranice. Jelikož je koncentrace napětí vyšší než koordinační napětí v důsledku rotace mřížky, může koncentrace napětí od nakupení dislokací silně ovlivnit otevření iniciující trhliny. Nakupení dislokací na rovinách {111} v měkkém zrnu FCC polykrystalického materiálu vyvolává nekompatibilitu deformace se sousedním zrnem. Dochází tak ke vzniku napětí podél směrů <111> v pevném zrnu. Výsledky byly v souladu s podpovrchovou iniciací trhlin v austenitické oceli s vysokým obsahem dusíku.

1 INTRODUCTION

Fatigue crack initiation is generally understood to occur on a specimen surface due to irreversible process of extrusion and intrusion through slip deformation [1]. Subsurface crack initiation in high-cycle fatigue, however, has been reported in high-cycle fatigue for α-titanium alloys at and below room temperature. The subsurface crack initiation site commonly shows a crystallographic facet. The facet plane was identified as (0001) by EBSD (electron backscatter diffraction) method [2]. The previous study [2] suggested that the strain incompatible at a boundary invited a cracking at lower peak stress in high-cycle fatigue. To understand this crack initiation mechanism, the concentrating local stress field and cracking should be made clear. Therefore, Taylor analysis was adopted firstly to evaluate the relaxation of the stress induced low-temperature yielding, since the primary slip systems activated for a tensile stress direction were indentified.

2 OUTLINE OF TAYLOR ANALYSIS

When a grain changes its shape, the deformation is achieved by operating slip systems. There are a number of their combinations to satisfy with the deformation. Only one combination should be chosen, so that minimum work principal is applied as

$$dw = \sum \tau_i \times \dot{\gamma}_i \qquad (i=1,2\cdots N) \qquad (1)$$

where dw is external plastic work rate, τ_i is resolved shear stress (CRSS) from i slip system, and $\dot{\gamma}_i$ is shear strain increment from i slip system. The minimum work would correspond to slip on as few systems as geometrically possible.[3]
Taylor factor M is given as

$$M = \frac{\sum \dot{\gamma}}{\dot{\varepsilon}} \qquad (i=1,2\cdots N) \qquad (2)$$

where $\dot{\varepsilon}$ is external strain increment. M represents shear strain increment needed to deform.
Since values of CRSS for primary slip systems in α-titanium are different each other, Taylor analysis was taken into each CRSS at low temperature (Tab.1; [4]). In the present model, the external plastic deformation (total shear strain increment) was evaluated, when a grain ideally coordinates the strain incompatible.

Tab.1: Ratios of critical resolved shear stress in major slip systems at 300 K.

Slip system	$\{10\bar{1}0\}<11\bar{2}0>$	$\{0001\}<11\bar{2}0>$	$\{10\bar{1}1\}<11\bar{2}3>$
Ratio	1	4	22

3 EVALUATION AND DISCUSSION

3.1 Tensile stress induced by restricted slip

The dislocation structure in the fatigued sample showed a multidirectional plastic deformation at lower stress level for α-titanium alloy.[6] Then Taylor analysis as applied to evaluate the activity of primary slips against applied stress. Figure 1 shows the dw with contoured map on that inverse pole figure. Lower dw are distributed in α=50~90 degrees where the grain is easy to deform. Even if the stress in a grain is generated due to a crystallographic orientation, it can be relaxed by own plastic deformation. The highest dw is at α=0 where the stress axis is normal to (0001), since the grain can hardly relax the stress. Activation of pyramidal slip is necessary to relax the stress as shown Fig.2. However no pyramidal slip was observed by transmission electron microscopy.[2] Fatigue cracks were initiated in the specimen interior at lower stress level and their origin was a crystallographic facet of (0001).[2,6] It suggests that tensile stress exists along <0001> in the grain. High CRSS of pyramidal slip may give a reason for the opening stress of microcrack.

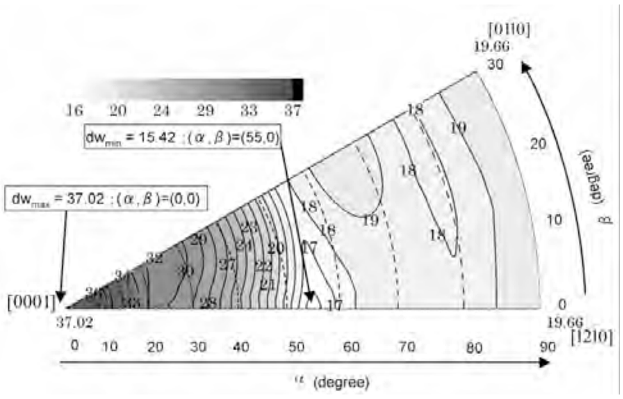


Fig.1: Dependence of external plastic work rate on tensile axis at 300 K.[4]

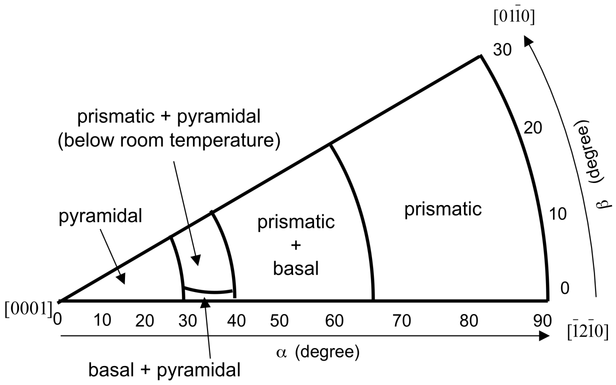


Fig.2: Schematic illustration of dominant slip systems for tension in α-titanium at low temperature.[4]

3.2 Strain incompatibility due to cyclic deformation

Piled-up dislocations intrinsically develop a stress concentration at the grain boundaries. Also the dislocations which go forward and backward on a slip plane under cyclic loading condition are often accompanied lattice rotation in the neighbor of the boundary except the case of direct transfer, and the lattice rotation extrinsically causes a stress concentration there. Although the shear stress due to plastic rotation was estimated as 3.7 x10^7 (Pa),[2] maximum of shear stress due to lattice rotation is 8.23 x10^3 (Pa) as shown in Fig.3. Thus the shear stress due to lattice rotation is much less than that due to piled-up dislocations.

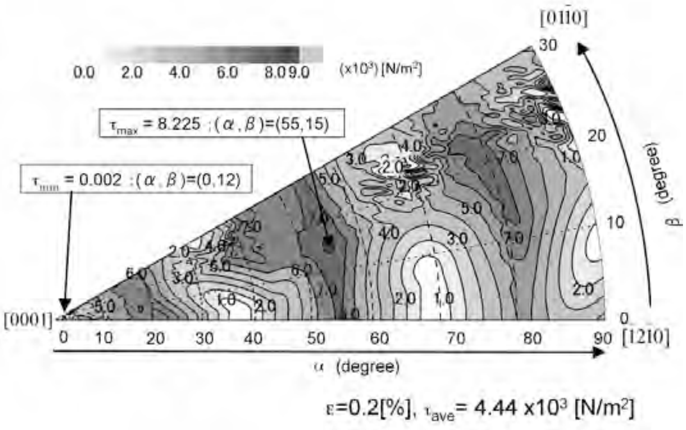
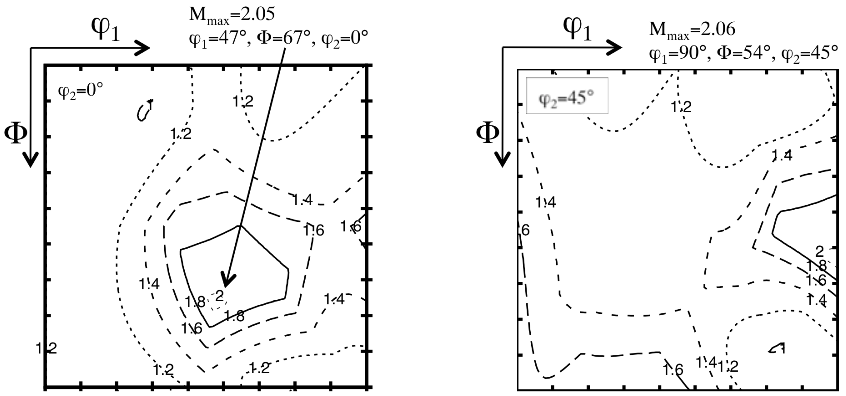


Fig.3: Stress concentration τ induced by lattice rotation at grain boundary.

3.3 Strain incompatibility between soft grain and hard one

The strain incompatibility between soft (yielded) grain and hard (elastic) one results from the difference of orientation in polycrystalline. The coordinated deformation model which describes homogenized deformation behavior between two grains was adopted to discuss this phenomenon.[8] When piled-up dislocations are developed in a soft grain, strain incompatible occurs near the grain boundary. At that time the coordinating deformation induced in the neighbor (hard) grain was analyzed. Taylor factor, M, which represents the difficulty of the coordinating deformation strongly depends on the orientation relationship between soft grain and hard one as shown in Fig.4. Dominant slip systems and induced stress direction were also evaluated in the case of hard to deform. The number of slip systems was three, and their shear strain rates were almost the same. The slip planes were different and new stress field was geometrically generated along <111> in the hard grain. These results agree to the subsurface crack initiation sites described in the reference [7] where a grain coordinate strain is incompatible due to piled-up dislocations on {111} in FCC polycrystalline such as high-nitrogen austenitic steel.



(a) (b)

Fig.4: Dependence of M in coordinating deformation on the orientation relationship between soft grain and hard one: (a) φ_2=0 degree and (b) φ_2=45 degree in the Euler space.

4 CONCLUSIONS

Taylor analysis was adopted to evaluate the relaxation of the stress induced low-temperature yielding. Major conclusions were as follows:

1) For dislocation structure such as pile-ups developed by high-cycle fatigue, the tensile stress is easily to accumulate along <0001> in α-titanium.
2) Stress concentration due to piled-up dislocations is larger than that due to lattice rotation.
3) When a grain coordinate strain is incompatible due to piled-up dislocations on {111} in FCC polycrystalline such as high-nitrogen austenitic steel, operation of three slip systems on independent plane each other resulted in hard to relax the strain incompatible.

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