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Microstructural heterogeneity in rate-dependent plasticity of multiphase titanium alloys

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ABSTRACT

Polycrystalline rate-dependent plasticity is found to originate from heterogeneous slip system/phase rate response. Micro-mechanism under low stress and low temperature (T < 0.3Tm) has been shown to be different from conventional rate sensitivity expectations. Hence the constitutive framework developed is dependent on the crystallographic orientation, properly capturing micro-scale anisotropic rate behaviour.

The intrinsic rate anisotropy of the HCP α prism and basal and BCC β phase slip systems in Ti-6242, recently determined from micro-pillar and crystal plasticity modelling, have been utilised to investigate the structural strain rate sensitivities of colonies, polycrystals, bimodal and basket weave microstructures.

The rate sensitivity of colony structures is dominated by the HCP α phase behaviour, at least for alloys containing up to ~20% volume fraction β phase, and is largely independent of β-lath orientation. The apparent anisotropy of a_1, a_2 and a_3 basal resolved shear stresses in Ti-6242 colonies is shown to originate from the local crystal stress states established as opposed to the $\alpha-\beta$ interfaces.

Texture and $\alpha-\beta$ morphology are shown to affect rate dependence and to corroborate that the basal rate sensitivity is stronger than that for prism slip in Ti-6242. Morphological effects are shown to affect rate dependence but not strongly, but the number of HCP α phase variants in basketweave structures is found to have a significant effect with higher numbers of variants leading to lower strain rate sensitivities. This is potentially important in designing alloys to resist cold dwell fatigue.

1. Introduction

The rate-dependent behaviour of a range of hexagonal close packed (HCP) metals at low homologous temperature ($T < 0.3T_m$) leads to significant creep, stress relaxation and the redistribution of stress, often over short time periods. In the context of near-α Ti alloys, it is of particular significance because of its role in the nucleation of dwell fatigue facets which are found to develop on basal planes oriented within about 10 to 15° normal to loading (Sinha et al., 2006). Even at low temperature (e.g., 20 °C), titanium alloys show strong strain rate-dependent material strength and deformation behaviour (Conrad, 1981) and the resulting rate dependence/creep behaviours are physically and industrially important since

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virtually all titanium components operate across the rate-sensitive temperature range (Adenstedt, 1949; Evans, 1987; Neeraj et al., 2000). Plastic strain developed by rate-dependent viscous ratcheting leads to slip accumulation and under conditions of stress dwell, leads to stress redistribution (or load shedding) in appropriately orientated grain pairs, shortening component life (the dwell debit) substantially (Bache, 2003). Compared to single phase metals, those of multi-phase tend to show higher strengths and a change to the strain rate dependence argued to be related to texture and microstructural morphology (Donachie, 2000; Welsch et al., 1993). Rate-dependent behaviour has been reported for single crystals, polycrystals and multiphase titanium alloys in the literature (Conrad, 1981; Welsch et al., 1993), and is therefore important for the industrially-useful near-α (e.g., Ti-6242) and α-β (e.g., Ti-6246). The former alloy much used in the aero-engine industry, for example, is known to show significant cold dwell fatigue debit.

Crystal orientation-dependent strain rate sensitivity, work hardening rate, and creep behaviour have been reported extensively in single crystalline materials. Inui et al. (1997) found that the critical resolved shear stress for <101> slip depended on the crystal orientation in single crystal TiAl, and they reported the strain rate sensitivity being crystal orientation dependent. At room temperature, strain rate sensitivity was found to be higher in a $[\bar{1}52]$-oriented crystal than that in the [021] direction. Guiu and Pratt (1966) found that the room temperature proportionality limit of strain to stress and work hardening rate of single crystal molybdenum depended remarkably on the crystal orientation. Similar crystal orientation-dependent work hardening/strain rate hardening has been observed in single crystal tungsten (Rose, 1962), single crystal iron (Spitzig and Keh, 1970), and single crystal Cu (Bonneville and Escaig, 1979). Orientation-dependent steady-state creep rate has been found in single crystals of γ' precipitation-hardened nickel-based superalloy (Leverant et al., 1973). Experiments on CMSX-4 nickel-base single crystal superalloy showed orientation-dependent creep deformation for tensile loading within 20° of the <001> direction (Rae and Reed, 2007). Crystal-orientation dependent strain rate/creep behaviour has been related to directional cross-slip operation (Bonneville and Escaig, 1979) or a process involving the nucleation, propagation and termination of a specific dislocation structure (Rae and Reed, 2007).

For HCP crystals, Weertman (1983) found polycrystalline and single crystal ice in a hard orientation led to creep rates about 500 times lower than that for soft glide. Orientation dependent room temperature yield stress has been found in single crystal ternary Ti3Al-V alloys (Umakoshi et al., 1993) and critical resolved shear stress (CRSS) for the {1010}<1210>-slip showed a violation of Schmid law. Gu et al. (1994) presented orientation-dependent cyclic deformation in single crystal high purity titanium; when orientations were favourable for double and multiple slip, cell structures were found and the cyclic strain hardening rate was high. Due to the orientation-dependence, the measurements of strain rate sensitivity were used to identify twinning and changes in deformation mechanisms in a Mg AZ31 alloy over a wide range of temperatures and grain sizes (Korla and Chokshi, 2010).

In single crystals of pure metals, the orientation effect on rate-dependent deformation was argued to be caused by dislocation kinks and jogs that depended on the orientation (Thornton and Hirsch, 1958). TEM studies have shown wavy dislocation networks in HCP basal slip but planar slip in prismatic slip systems in single crystal Ti-Al alloys (Williams et al., 2002). This was also observed in a Ti-6242 alloy (Jun et al., 2016b; Zhang et al., 2016c) for which the intrinsic strain rate sensitivities for the basal and prismatic slip systems are very different, and that single crystals of Ti-6242 therefore show strongly anisotropic strain rate sensitivity. In addition, the (bcc) β phase within colonies of Ti-6242 has also been shown to be rate sensitive at low (20 °C) temperature (Zhang et al., 2016b).

It is reasonable, therefore, to anticipate that strain rate sensitivity is also dependent on crystallographic texture in polycrystals, such that it may vary when texture evolves (Canova et al., 1988). The strain rate sensitivity exponent m (where $m = \frac{d\log\sigma}{d\log\dot{\varepsilon}}$) for textured ultrafine-grained aluminium films (with mean grain size ~275 nm) was found to be 0.017, more than six times lower than that for the non-textured film ($m = 0.103$) (Izadi and Rajagopalan, 2016). As a result, flow stress increased by 14% for (110) textured films when strain rate increased from $\sim 7\times10^{-6}\,\mathrm{s}^{-1}$ to $5\times10^{-3}\,\mathrm{s}^{-1}$ whereas this was amplified by more than 90% over a similar strain rate range for non-textured films. The mechanistic link between single crystal strain rate sensitivity to that for textured polycrystals has not yet been thoroughly addressed.

In addition to texture, microstructural morphology in multiphase alloys also leads to strong heterogeneous stress and plastic strain fields and hence local mechanical behaviour, including grain-level stress redistribution from rate-dependent deformation (Evans, 1998). Differing morphological microstructures can be obtained by thermomechanical processing (Weiss and Semiatin, 1998, 1999). For example, aligned α colonies may be formed as a result of slow cool, with the size of the aligned α colonies set by the prior β grain size (Conrad et al., 1961). As shown by Lutjering (1998), varying the cooling rate from the β phase field on lamellar microstructures of Ti-6242 can lead to a colony structure (1 °C/min) or to basket weave structure (8000 °C/min). By control of deformation and recrystallization in the $\alpha+\beta$ phase field, where the recrystallization temperature determines the volume fraction and size of equiaxed primary α phase, it is possible to achieve bimodal/duplex microstructures, showing equiaxed primary α grains surrounded by secondary α laths and β plates.

The morphological structure established through cooling rate, whether globular, colony, basket-weave, Widmanstätten or bimodal equiaxed, substantially affects the creep response and rate-dependent yield strength. Conrad and Wiedersich (1960) established the relationships between cooling rate and creep resistance in Ti-25Al-10Nb-3V-1Mo. Generally, the β solution-treated colony-type (slow cooled) microstructure showed superior creep resistance, and the strain-rate dependence of room temperature tensile strength was dependent on the microstructure. Cho et al. (1988) reported that cooling rates from the solutionizing temperature had a major influence on the subsequent creep rates in Ti-6242. Higher cooling rate can introduce decreasing α-β spacing, which has been argued to lead to improved creep resistance. It can result in finer α lath spacing in Ti-6242, and improved creep properties (Viswanathan et al., 2002). Miller et al. (1987) have studied the