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Competition between dynamic recovery and recrystallization during hot deformation for TC18 titanium alloy

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ABSTRACT

The competition between dynamic recovery (DRV) and recrystallization (DRX) during hot deformation has been investigated in the present paper. Isothermal compression experiment of TC18 titanium alloy was conducted for verification. The hot deformation mechanism for TC18 alloy has been identified as dislocation evolution from the stress exponent correspondence. Suitable descriptions to dislocation evolution under DRV/DRX have been obtained and validated by stress variation with DRX critical strain as the transition. Work-hardening behaviors correspond to the competition between DRX/DRV and segmented functions were constructed to describe the variation. The influence of α/β phase transformation and DRX evolution on dislocation evolution and work-hardening behaviors has been characterized with the Kocks–Mecking model developed. Power dissipation efficiency and microstructure observation were utilized to demonstrate the dependence of dynamic softening mechanism. The β necking phenomenon in DRX grains has been associated with the periodic competition between DRX and DRV.

1. Introduction

The thermomechanical coupling process has generated considerable interests from the plasticity research community and industry owing to the integration of plastic forming and microstructural evolution. It is a complicated task to clarify the hot deformation process influenced by two competing mechanisms, work-hardening effect from continuous straining and subsequent softening effect such as dynamic recrystallization (DRX) and dynamic recovery (DRV) [1]. The stress–strain characteristics and microstructural evolution during hot deformation significantly correspond to the competition behaviors between DRV and DRX.

The flow stress increases with strain until the saturated stress achieved during hot deformation undergoing DRV [2]. While softened by DRX, the flow curves exhibit obvious decreasing trend from the stress peaks after hardening stage [3]. The flow curve shape difference from competition between DRV and DRX have been utilized as the traditional identification method for dynamic softening mechanism [4,5]. With the formation of equiaxed or spheroidized non-distortion grains as the significant sign for DRX, deformed characteristic has been reserved in the microstructures softened by DRV, different from the microstructural reformation by DRX [6]. Various stress–strain behaviors and microstructure evolution directly determine the processing difficulty and ultimate mechanical properties while component forming [7]. Therefore, it has been of fundamental and technological importance to investigate the competition behavior between DRV and DRX during high-temperature processing.

Work-hardening and dynamic softening effect has been considered interdependent because the driving force for dynamic softening is provided by distortion energy from work-hardening process and the softening effect makes the continuous strain possible to induce subsequent hardening. The correlation between work-hardening and dynamic softening effect has already been focused on by several papers [8–12]. Jorge et al. [8] demonstrated the constitutive relationship from the competition between work-hardening and DRV for the small deformation of ultra-low carbon steel. Corresponding dislocation evolution was described by the Kocks–Mecking (K–M) and Estrin–Mecking (E–M) relations and a transition, characterized as the DRX softening onset, could be observed from work-hardening ($\theta \equiv \partial\sigma/\partial\varepsilon$) curves. Zhang et al. [9] described the hot deformation behaviors of a nitride strengthened martensitic heat resistant steel through the combination of work-hardening curves and Arrhenius constitutive model. DRX, DRV, metadynamic recrystallization (MDRX) and dynamic strain induced transformation (DSIT) phenomena have been identified with the verification by microstructure observation. Lin et al. [10,11] systematically investigated the influence of strain, strain rate and temperature on microstructural evolution during hot compression of 42CrMo steel. The correspondence of DRX and/or DRV has been employed to discuss the morphology and distribution of newly-formed grains and the relationship between grain size and the

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Zener–Hollomon parameter has been obtained. Zurob et al. [12] integrated the interdependence of DRV, DRX, work-hardening and phase precipitation to characterize the hot deformation behavior of microalloyed austenite steel. A comprehensive but complex model has been proposed to track the DRX nucleation, growth process and the corresponding stress variation from softening. Although the association between work-hardening and dynamic softening effect has been characterized in microstructural and mechanical perspective, suitable quantitative description to the correlation has not been constructed between work-hardening and dynamic softening effect. The competitive but dependent relationship between DRX and DRV results in the complexity of flow behavior and microstructural evolution during hot deformation. A comprehensive investigation is required to demonstrate this dependence from internal variables.

In the present paper, the competition between DRV and DRX during hot deformation has been quantitatively investigated under the experimental verification by isothermal compression of TC18 titanium alloy. The hot deformation mechanism for TC18 alloy has been identified from the stress exponent correspondence. The applicability of the Kocks–Mecking and Estrin–Mecking relations on the description to dislocation evolution has been discussed and validated by corresponding stress variation with DRX critical strain as the transition. The influence of α/β phase transformation and DRX evolution on dislocation evolution has been characterized with the Kocks–Mecking model developed. The dependence of work-hardening behavior on dynamic softening mechanisms has been demonstrated by segmented functions. Power dissipation efficiency distribution and microstructure observation were utilized to assist the analysis on work-hardening variation. The necking phenomenon in β grains by DRX would be explained by the softening competition.

2. Materials and experimental procedures

TC18 (Ti–5Al–5Mo–5V–1Cr–1Fe) titanium alloy, known as Ti55511, is a type of near-β titanium alloy that possesses high strength and toughness, low density, and good corrosion resistance. Therefore, this titanium alloy has been widely utilized to fabricate load-bearing components in the aerospace industry like aircraft landing gears [13].

In the present study, near-β titanium alloy was selected to investigate the interdependence between DRX and DRV owing to its unique softening behavior, recrystallization aided by recovery, during hot deformation [14]. β matrix with BCC structure is considered with high stacking fault energy (SFE), which could accelerate dislocation climbing and crossing-slipping for DRV process [14]. A continuous DRV existence could be maintained before DRX onset during hot deformation of near-β titanium alloy. Therefore, the competitive behavior between DRV and DRX could be comprehensively investigated at a larger strain and/or stress range for hot deformation of near-β titanium alloy.

The chemical compositions (wt%) of experimental alloy have been given as follows: Al 5.15, Mo 4.96, V 4.75, Cr 0.95, Fe 1.04, Ti bal. The α/β transus temperature was measured as 885 °C by using the metallographic observation method.

As-received experimental material has been forged by multi-directional upsetting to avoid anisotropy and the wrought billet was thermally treated at 800 °C for 1 h to improve the homogeneity and stability. The initial microstructure of TC18 alloy before deformation is shown in Fig. 1 with equiaxed a phase distributed uniformly in beta phase. Cylinders of TC18 alloy with a diameter of 8 mm and height of 12 mm were machined from the annealed billet. Isothermal compression experiment was conducted on a Gleeble-1500D thermo-mechanical simulator. Six different temperatures (800, 820, 840, 860, 880 and 900 °C) and six different strain rates (0.0005, 0.001, 0.01, 0.1, 1 and 10 s^{-1}) were utilized. The heat-holding time before isothermal compression was designed as given in Table 1, to guarantee complete heating and avoid undesired grain growth under higher temperatures. The final deformation degree was 80%. The specimens were immediately quenched by cold water to reserve deformed microstructures after each experiment. Then the deformed specimens were sliced along the compression axis section for microstructural analysis. After polished mechanically and etched in Kroll's reagent, the exposed surfaces were observed by an OLYMPUS-PMG3 optical microscope.

3. Results and discussion

Fig. 2(a) exhibited the flow curves under different temperatures and strain rates from isothermal compression experiments. Three typical stress variation stages in flow curves could be divided as demonstrated in Fig. 2(b). Plastic behavior is determined in many cases by the evolution of dislocations while deforming. The stress is elevated rapidly on work-hardening stage from dislocation multiplication and continuous trapping by existing obstacles [15]. With the distortion storage satisfied from work-hardening stage as the driving force for dynamic softening, the stress would be relieved and decrease with strain as the rearrangement and annihilation of dislocation results in the density drop [16]. When the dislocation proliferation and annihilation achieve dynamic balance, the stress variation from work-hardening and dynamic softening would maintain stable with strain as shown in steady flowing state.

Obvious stress decrease could be observed from most of flow curves and the three stress variation stages could be clearly identified. Only curves with high temperatures as 900 °C and low rates as 0.0005 s^{-1} exhibited the steady trend at saturated values, indicating the occurrence of DRV. Titanium alloys are considered parameter-sensitive because of their significant hardening effect [17]. Sufficient distortion storage from strong hardening guarantees

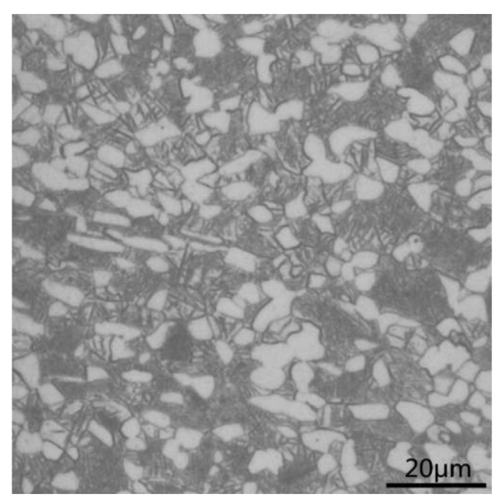

Fig. 1. Original microstructure of TC18 titanium alloy consisting of equiaxed α grains in the β matrix.

Table 1
Heat-holding time before isothermal compression of TC18 alloy under different temperatures.

Deformation temperature (°C)	800	820	840	860	880	900
Holding time (min)	9	9	9	8	7	6