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Independence of work hardening and precipitation strengthening in a nanocluster strengthened steel

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ABSTRACT

Work hardening and precipitation strengthening are two important strengthening methods that closely associate with dislocation density. Here, a new class of nanocluster strengthened steel with a tensile strength of ~2.02 GPa and an elongation of ~7% is developed through a combination of work hardening and precipitation strengthening. The work hardening is strongly dependent on the dislocation density induced by thermomechanical treatments while there is no effect for dislocation density on precipitation strengthening. The work hardening and precipitation strengthening are independent and can be controlled separately. The strengthening effects of nanoscale precipitates are quantitatively analyzed and assessed.

1. Introduction

Precipitation strengthening plays an important role in the design and fabrication of advanced structure materials with superior mechanical properties and strong resistance to radiation damage [1–8]. With increasing unprecedented environmental challenges, advanced ultra-high strength steels strengthened by nanoscale precipitates have been developed [9]. Precipitation strengthening requires an optimized combination of size, number density and distribution of precipitates to yield the best combination of properties, such as yield strength, hardness and ductility [10–13]. The properties of the precipitates are remarkably dependent on the thermomechanical treatments [14,15]. At the same time, Thermomechanical treatment can also change dislocation patterns, leading to work hardening that is another strengthening mechanism [16,17]. Thus, dislocations may play three folds of roles. The first one is work hardening similar with that in the traditional alloys without nanoscale precipitates. The second one is the effect of dislocation on the precipitation of nanoscale particles during aging. The last one is the interaction between dislocations and nanoscale precipitates during deformation.

Many studies on the effect of dislocation on the mechanical properties have been carried out. Tsuchiyama et al. [18] have investigated the behavior of deformation and dissolution of ε-Cu particles. They found that dislocation shearing at particle tip causes a dynamic partitioning of Cu atoms from precipitates into the matrix. The number of the particles decreases after a certain amount of cold working, and the dissolution of the dispersed particles occurs as reported in cold worked aluminum alloys [19,20] and cold draw pearlite wires [21]. A fatigue test of 1.5 at% Cu bearing interstitial-free (IF) steel shows that maximum stress gradually decreases during the cyclic loading under a constant strain [22]. In the early stage of deformation, the precipitation strengthening is effective. However, the anomalous effect emerges after severe plastic deformation or cyclic stress loading. Thus, it is vital to understand the relationship between work hardening and precipitation strengthening, since both are associated with dislocation patterns. This understanding is the most important prerequisite for the preparation of nanoscale precipitate-strengthened

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steels with a good combination of high strength and high ductility.

In this paper, nanocluster strengthened steels with different dislocation density were prepared. The nanoscale precipitates and their contributions on the mechanical properties were studied by small-angle neutron scattering (SANS) and theoretical calculations, respectively. Combining the mechanical properties and the theoretical calculation of precipitation strengthening, a thorough study of the effect of dislocation on the precipitation of nanoscale cluster and the correlation between work hardening and precipitation strengthening was conducted.

2. Experiment

A nanocluster strengthened steel with a nominal composition of Fe-1.5Mn-2.5Cu-4Ni-1Al-0.005B-1.5Mo-0.05Nb-0.1Ti-1.5W-0.08C-0.5Si (wt%) was selected for the experimental investigation. The cast ingots with a weight of ~50 kg were obtained by vacuum induction melting with magnetic stirring to ensure homogeneous distribution of alloying elements. The cast ingots were rolled to a total reduction of 80% with a starting temperature of 900 °C and final temperature of 800 °C through 8 passes. The final thickness of the as-rolled steel plate was 12 mm. The as-rolled sample is labeled as AR. To obtain different dislocation densities, AR steel was then cold rolled to 2 mm after removing the surface oxides (labeled as ACR). One piece of ACR steel was then annealed at 900 °C for 2h and then water-quenched. This treatment plays two roles. One is the solid solution treatment of the steel to make the Cu distribute in the matrix uniformly. The other role is to reduce the dislocation density. The as-annealed specimen is labeled as ACR-SS. And then all the samples, AR, ACR and ACR-SS were aged at 500 °C for 5h. The aged samples are labeled as AR-AG, ACR-AG and ACR-SS-AG, respectively. In order to quantitatively evaluated dislocation density by XRD, the reference sample (RS) was prepared through recrystallizing the ACR steels at 1000 °C for 1h and stress relief annealing at 750 °C for 10h.

Tensile tests along the rolling direction of the samples were conducted on an Instron 5565 testing machine at a strain rate of $10^{-3}s^{-1}$. The gauge length, width and thickness of the tensile specimens were 12.5 mm, 4 mm and 1 mm, respectively. Three specimens were tested in the same condition and the average values were reported. The yield strength is determined with the 0.2% offset plastic strain method.

Optical microscopy (OM) and transmission electron microscopy (TEM) were used to characterize the microstructure of the specimens. The TEM samples were prepared by twin-jet polishing using a solution of 5% perchloric acid and 95% ethanol at −20 °C. The nanoscale precipitates were characterized using small angle neutron scattering (SANS) at the China Mianyang Research Reactor

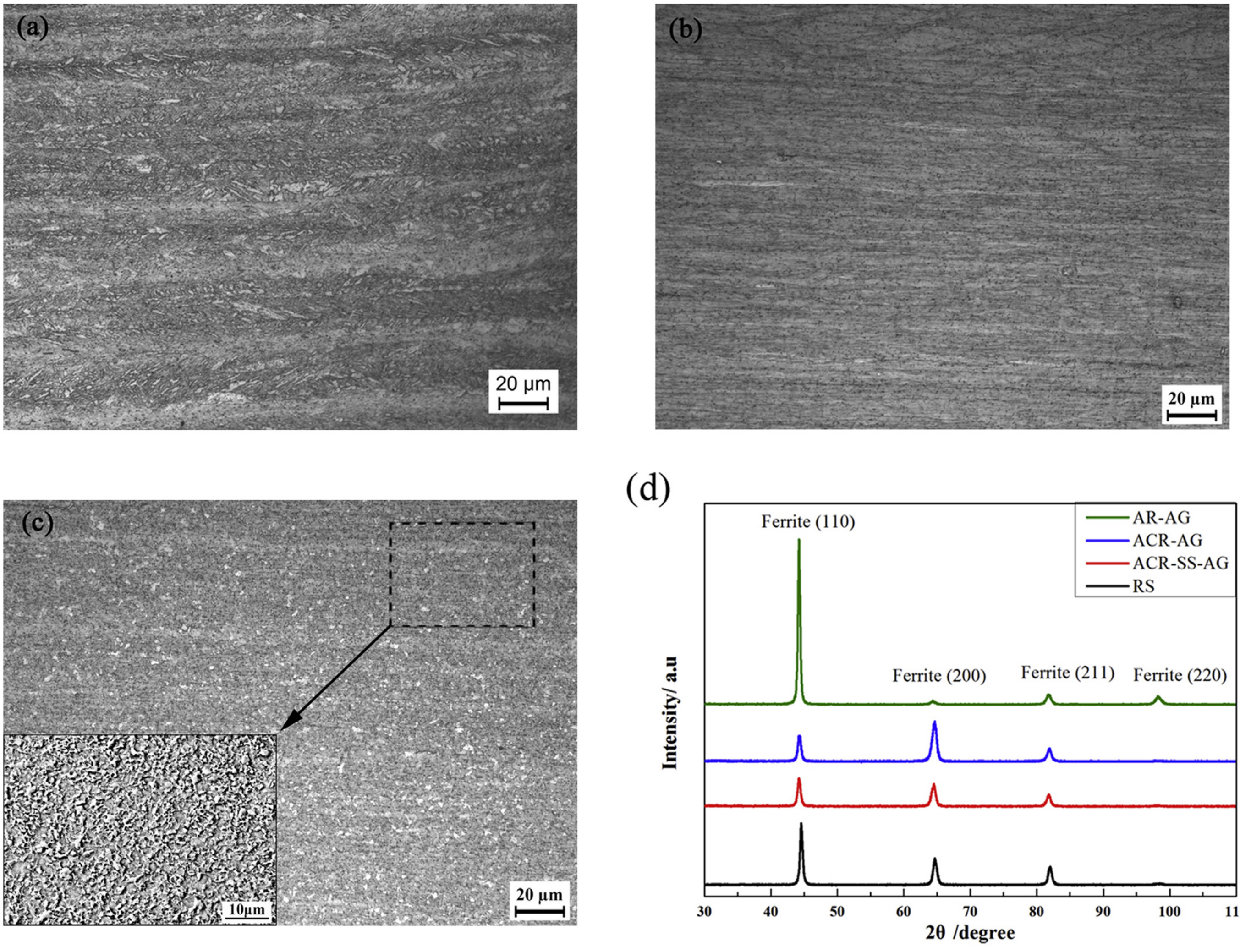

Fig. 1. The optical microstructures of (a) AR-AG steel, (b) ACR-AG steel, (c) ACR-SS-AG steel and (d) the X ray diffraction spectra of all the aged specimens.