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Research Paper

Texture evolution and mechanical anisotropy of biomedical hot-rolled Co–Cr–Mo alloy

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ABSTRACT

Crystallographic textures and their effect on the mechanical anisotropy of a hot-rolled biomedical Co–Cr–Mo alloy were investigated. The hot-rolled Co–28Cr–6Mo–0.13N (mass%) alloy examined here exhibited a monotonic strength increment following hot-rolling reduction, eventually reaching a 0.2% proof stress of 1400 MPa while maintaining acceptable ductility (>10%). The dominant hot-rolling texture was a brass-type component, which is characterized by the alloy's peculiarly low stacking fault energy (SFE) even at hot rolling temperatures, although the minor peaks of the near copper component were also identified. However, because of the onset of dynamic recrystallization (DRX) during the hot rolling process, the texture intensity was relatively weak even after 90% hot rolling, although the grain refinement originating from the DRX was not significant (the “less active DRX” condition increased the strain accumulation during the process, resulting in high-strength samples). The weakened texture development resulted in negligible in-plane anisotropy for the hot-rolled specimen strength, when the specimens were tensile strained in the rolling direction (RD) and transverse direction (TD). The elongation-to-failure, however, exhibited a difference with respect to the tensile loading axis. It is suggested that the ductility anisotropy is closely related to a strain-induced γ (fcc) \rightarrow ϵ (hcp) martensitic transformation during tensile loading, resulting in a difference in the proportion of quasi-cleavage fracture surfaces. The obtained results will be helpful in the development of high-strength Co–Cr–Mo alloy plates and sheets, and have implications regarding plastic deformation and texture evolution during the hot rolling of non-conventional metallic materials with low SFE at elevated temperatures, where planar dislocation slips of Shockley partial dislocations and thermally activated process interplay.

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1. Introduction

Along with titanium alloys (Ti–6Al–4V, β titanium alloy, etc.) and austenitic stainless steel (e.g., 316L), Co–Cr–Mo alloys have been applied in various biomedical devices. For example, they have been used as bearings in artificial hip joints, rods for spinal-instrumentation surgery, bone plates, and screws (Chiba et al., 2007; Niinomi et al., 2012; Yoshihara, 2013). This is because of the excellent corrosion and wear resistance of these alloys compared with other metallic biomaterials. In recent years, the use of high-strength Co–Cr–Mo alloys to improve the durability of biomedical devices has attracted considerable attention, and we recently performed intensive studies on the strengthening of these biomedical alloys through thermomechanical processing (Chiba et al., 2005; Mori et al., 2012; Yamanaka et al., 2012a, 2011). We focused on dynamic recrystallization (DRX), which occurs during hot deformation at elevated temperatures above ~ 1273 K (Yamanaka et al., 2012a, 2012b, 2011, 2009). Hence, systematic compression testing revealed that DRX significantly reduces grain size, because of the peculiar low stacking fault energy (SFE) of these alloys at hot deformation temperatures (Yamanaka et al., 2012b, 2009); a minimum grain size of $0.6 \mu\text{m}$ was obtained using hot-compression testing at 1323 K with a strain rate of 0.1 s^{-1} . A considerably lower strain than that seen in severe plastic deformation (equivalent strain, $\epsilon_{\text{eq}} > 4$) (Tsuji and Maki, 2009) is sufficient for the production of bulk nanostructures with grain sizes of less than $1 \mu\text{m}$, and the developed Co–Cr–Mo alloys exhibit a superior tensile yield stress (1400 MPa), while maintaining an acceptable elongation-to-failure value of 10% (Yamanaka et al., 2012a).

Although such a DRX-mediated advanced processing method is interesting from both academic and industrial points of view, the actual Co–Cr–Mo alloy manufacturing process consists of multipass hot deformation, involving rolling, swaging, drawing, etc., with a relatively small reduction per pass (typically $\sim 20\%$). This is because of the high deformation loads of the alloys. Therefore, the significant DRX-mediated grain refinement mentioned above generally cannot be employed in conventional production processes, since critical strains for DRX initiation under each deformation condition exist ($> 20\%$) (Yamanaka et al., 2012b). However, multipass “low-strain-per-pass” hot deformation, under which DRX occurs less significantly, has not been addressed in detail.

Further, our previous research revealed that Co–Cr–Mo alloy strength can also be dramatically improved through hot rolling, which is a typical multipass hot deformation process (Mori et al., 2012). The observed strengthening during hot rolling is associated with texture evolution. As is well known, crystallographic textures develop through successive material elaboration stages, such as solidification, plastic deformation, and phase transformation. In particular, deformation textures evolve in accordance with dislocation and twinning

activity, and the rolling textures of a variety of metals and alloys have been intensively investigated. The plastic deformation of metallic materials with face-centered cubic (fcc) structures generally exhibits SFE dependence. High-SFE metals such as Al, Cu, and Ni develop a copper or pure metal texture characterized by a strong β -fiber, with increasing intensity from the brass component over the S component to the copper component (El-Danaf et al., 2000; Humphreys and Hatherly, 2004; Ray, 1995; Smallman and Green, 1964). In contrast, low-SFE materials develop a brass or alloy texture with lower intensity on the copper component and increased intensity on the brass and Goss components (i.e., the fcc α -fiber). This is possibly due to operating deformation twinning (Vercammen et al., 2004).

Typically, the SFE increases with increasing temperature and exhibits extremely high values at elevated temperatures. However, unlike conventional fcc materials, the biomedical Co–Cr–Mo alloys investigated in the present study have quite low SFE even at the elevated temperatures at which hot deformation is conducted (> 1273 K). In such a case, the plastic deformation behavior is quite peculiar: the slipping of Shockley partial dislocations (instead of perfect dislocations) plays a dominant role during hot deformation, resulting in planar dislocation structures and texture formation variations. Therefore, in addition to its practical importance, elucidating the texture evolution of these materials is scientifically interesting, because no other materials exist that display interaction between planar dislocation slips of Shockley partial dislocations and the dramatic microstructural evolution associated with dynamic restoration processes.

In this work, we have succeeded in realizing a marked strengthening of biomedical Co–Cr–Mo alloys by employing multipass “low-strain-per-pass” hot rolling (Mori et al., in revision). The reported strength level is significantly higher than those of conventional alloys, including previously reported hot-rolled samples (Mori et al., 2012). The aim of this work is to describe the crystallographic textures of this high-strength Co–Cr–Mo alloy during the hot rolling process. The effect of this evolution on the mechanical anisotropy is also discussed.

2. Material and methods

2.1. Sample preparation

A Ni-free Co–29Cr–6Mo (mass%) alloy with 0.13-mass\% nitrogen was prepared using high-frequency vacuum induction melting. Table 1 lists the chemical composition of the prepared alloy, which was determined through conventional chemical and gas analyses (Yamanaka et al., 2013). Nitrogen was added to stabilize the γ phase and to improve both the alloy strength and ductility (Yamanaka et al., 2014, 2013). An ingot of the fabricated alloy, weighing $\sim 30 \text{ kg}$ ($\sim 150 \text{ mm}$ in diameter), was subjected to a

Table 1 – Chemical composition of Co–28Cr–6Mo–0.13N alloy used in this study (mass%).

Co	Cr	Mo	N	Ni	Mn	Si	Fe	C
Bal.	28.20	5.92	0.126	0.00	0.62	0.50	<0.10	0.04

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