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Micropillar compression deformation of single crystals of $Co_3(Al,W)$ with the $L1_2$ structure

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ABSTRACT

The compression deformation behavior of single-crystal micropillars of $L1_2$–$Co_3(Al,W)$ has been investigated at room temperature as a function of pillar size and crystal orientation. The critical resolved shear stress (CRSS) obeys an inverse power-law scaling against pillar size and is independent of orientation. With the bulk CRSS value of $Co_3(Al,W)$ at room temperature estimated by extrapolating the size dependence of CRSS for micropillars, comparison of high-temperature strength is made on the CRSS values for $Co_3(Al,W)$ and Ni_3Al-based compounds. $Co_3(Al,W)$ has turned out not to be strong enough to provide excellent high-temperature strength for Co-based superalloys, at least for ternary composition.

The discovery of the γ'-$Co_3(Al,W)$ phase with the $L1_2$ structure in the Co–Al–W ternary alloy system by Sato et al. [1] has launched a new era of the development of high-temperature structural materials. The γ'-$Co_3(Al,W)$ phase coherently precipitates in the γ-Co (face-centered cubic (fcc) structure) solid-solution phase, resulting in a $\gamma + \gamma'$ two-phase microstructure with a regular array of cuboidal γ' precipitates, which resembles the typical microstructure of Ni-based superalloys strengthened by the γ'-Ni_3Al phase [1]. Indeed, these $\gamma + \gamma'$ two-phase alloys called Co-based 'superalloys' have demonstrated superior high-temperature strength when compared to conventional Co-based alloys strengthened by solid-solution hardening and carbide precipitation without cuboidal γ' precipitates [1–3]. We have recently investigated the deformation behavior of polycrystals of $Co_3(Al,W)$, the constituent phase of Co-based alloys, revealing that while the yield stress rapidly decreases with the increase in temperature at low temperatures, it increases anomalously with temperature only in a narrow temperature range at high temperatures (950–1100 K) [4,5]. TEM analysis has indicated that the yield stress anomaly is due to cross slip of superpartial dislocations with $\boldsymbol{b}$ (Burgers vector) $= 1/2[\bar{1}01]$ from (111) to (010) planes [6,7] as in many other $L1_2$ intermetallic compounds based on Ni_3Al, although these Ni_3Al-based $L1_2$ intermetallic compounds are known to exhibit the yield stress anomaly in a much wider temperature range so as to start from a lower temperature such as liquid nitrogen temperature, especially in ternary alloys [8–10]. Since the occurrence of yield stress anomaly in the constituent γ' phase is important for the strength of $\gamma + \gamma'$ two-phase alloys at high temperatures, comparison of the strength of $Co_3(Al,W)$ with those with Ni_3Al-based $L1_2$ compounds should be made to see how significantly $Co_3(Al,W)$ contributes to the strength of Co-based superalloys especially at high temperatures. However, the critical resolved shear stress (CRSS) has not been available for $Co_3(Al,W)$ due to the difficulties in preparing single crystals of the γ'-$Co_3(Al,W)$ single-phase large enough for the study of plastic deformation [11].

In recent years, however, a method based on compression testing of small pillars of single crystals of the order of micrometer size, which can be prepared from relatively small crystal grains in polycrystals by focused ion beam (FIB) machining, has been developed and opened a way to measure CRSS values of alloys even if large single crystals are unavailable [12–16]. It has been known that the CRSS values of single-crystal micropillars in fcc and body-centered cubic (bcc) metals decrease with the increase in pillar size, obeying an inverse power-law scaling [17–20]. The decrease in CRSS is considered to continue until the pillar size reaches a critical value, where the CRSS value corresponds to that measured in a bulk form [17–20]. Then, the CRSS value in the bulk form can be estimated by extrapolating the inverse power-law scaling of the CRSS values obtained in the micropillar form to the critical micropillar size. For many different metals with the fcc structure, on which the $L1_2$ structure is based, the critical size has been reported to be in the range of 20–

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30 μm [12,17,18], while Uchic et al. reported that the critical size for $L1_2$–$Ni_3(Al,Ta)$ is 42 μm at room temperature [12]. However, this critical size value obtained for $L1_2$–$Ni_3(Al,Ta)$ may not be used directly for $L1_2$–$Co_3(Al,W)$, in view of the fact that the onset temperatures for yield stress anomaly are quite different for these two $L1_2$ compounds (77 K and 950 K respectively for $Ni_3(Al,Ta)$ [21] and $Co_3(Al,W)$ [4]). Cross slip of superpartial dislocations from (111) to (010) planes frequently occurs so as to give rise to yield stress anomaly even at room temperature for $Ni_3(Al,Ta)$, while such cross slip is unlikely to occur at room temperature for $Co_3(Al,W)$. This indicates the necessity to investigate the size dependence of CRSS of micropillars of an $L1_2$-compound, in which yield stress anomaly is absent at room temperature and the bulk CRSS value of which can be obtained in large-sized single crystals, in order to deduce a critical pillar size suitable for the evaluation of the bulk CRSS value of $Co_3(Al,W)$. Binary stoichiometric Ni_3Al can be used for this purpose, since large single crystals are available and the yield stress anomaly starts just above room temperature [8].

In the present study, we investigate the plastic deformation behavior of single-crystal micropillars of $Co_3(Al,W)$ by compression tests as a function of specimen size and crystal orientation at room temperature, in order to estimate the bulk CRSS value from the size dependence of CRSS for single-crystal micropillars and to compare the deduced bulk CRSS value with those of other Ni_3Al-based $L1_2$ compounds.

Polycrystalline ingots with a nominal composition of Co-12 at.% Al-11 at.% W and Ni-25 at.% Al were prepared by arc-melting under an Ar gas flow. Polycrystals of $Co_3(Al,W)$ were annealed at 1123 K for 168 h followed by furnace cooling. Single crystals of the stoichiometric Ni_3Al were grown with an optical floating-zone furnace [22]. Single-crystal micropillars of $Co_3(Al,W)$ and Ni_3Al with a square cross-section having an edge length (1–10 μm) and an aspect ratio of 2–3 (Fig. 1a) were fabricated by the FIB technique. Single-crystal micropillars of $Co_3(Al,W)$ were machined from crystal grains whose orientation was determined by electron back-scatter diffraction (EBSD), while those of Ni_3Al were machined from bulk single crystals whose orientation was determined by the X-ray back reflection Laue method. Bulk specimens of Ni_3Al for compression tests with approximate dimensions of $2 \times 2 \times 5\ mm^3$ were cut from the single crystals by electro-discharge machining. The compression-axis orientations investigated were $[\bar{2}56]$ and $[\bar{1}36]$ for $Co_3(Al,W)$, and $[\bar{1}23]$ for Ni_3Al, as shown in Fig. 1b. Compression tests for single-crystal micropillars of $Co_3(Al,W)$ and Ni_3Al and for bulk single crystals of Ni_3Al were conducted at a strain rate of $10^{-3}\ s^{-1}$ at room temperature. Micropillar compression tests were conducted with a flat punch indenter tip on a Shimadzu MCT-211 micro compression tester. Deformation microstructures were observed by scanning electron microscopy (SEM).

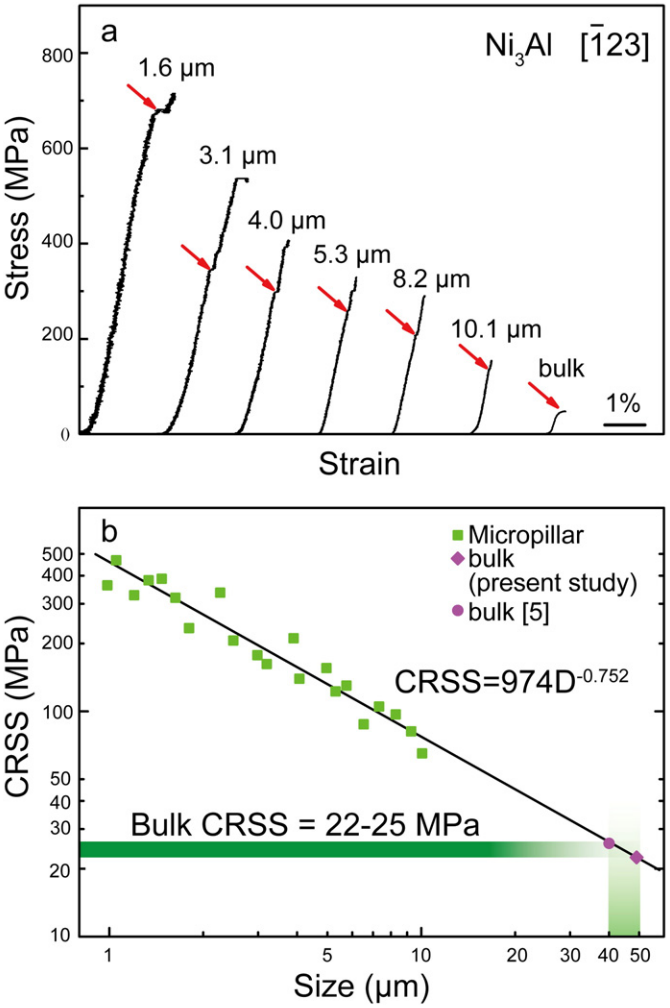

Fig. 2. (a) Selected stress-strain curves of Ni_3Al obtained for micropillar specimens as well as for a bulk specimen. The loading axis orientation is $[\bar{1}23]$. (b) Micropillar size dependence of the CRSS values for $\{111\}\langle\bar{1}01\rangle$slip in Ni_3Al.

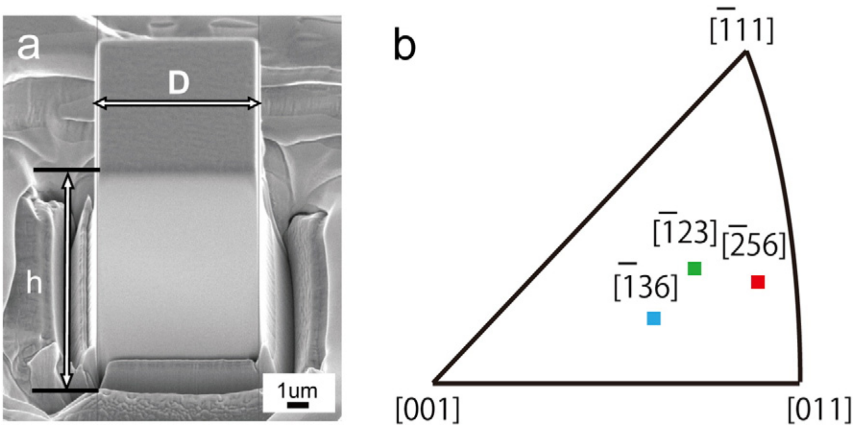

Fig. 1. (a) SEM secondary electron image of a single-crystal micropillar of $Co_3(Al,W)$ before compression. (b) Loading axis orientations of the single crystals of $Co_3(Al,W)$ and Ni_3Al.

Fig. 2a shows selected stress-strain curves for bulk single crystals and micropillars of Ni_3Al. The flow stress of the micropillars increases with decreasing pillar size and is considerably higher than that of bulk single crystals. Strain bursts, which are most likely associated with an avalanche-like collective motion of dislocations [23], occur in the stress-strain curves for all micropillars investigated. The yield stress for micropillars is thus determined as the stress at which the first strain burst occurs. Slip trace analysis has confirmed that slip on $(111)[\bar{1}01]$, the most highly stressed system, is operative for both bulk single