Effect of scanning strategy on texture formation in Ni-25 at.%Mo alloys fabricated by selective laser melting

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HIGHLIGHTS
• Fabrication of Ni-25 at.%Mo product was succeeded by the selective laser melting.
• Texture development can be controlled by changing the scanning strategy of the laser.
• Aligned crystal orientation along the build direction can be varied in \(\langle 001\rangle\) or \(\langle 101\rangle\).
• Controlling mechanism of the texture was clarified by microstructure observation.

GRAPHICAL ABSTRACT

ABSTRACT
Variations in the crystallographic texture in Ni-25 at.%Mo alloys fabricated by selective laser melting with different scanning strategies were designed for the first time. Single-crystalline-like texture with a short-range order of Mo atoms can be produced via bidirectional scanning along one axis (X-scan) and bidirectional scanning with a 90° rotation in each layer (XY-scan), while only fiber texture was formed in bidirectional scanning with a 67° rotation (Rot-scan). The aligned crystal orientation along the build direction can be varied by the scanning strategy; \(\langle 001\rangle\) is preferred in the XY- and Rot-scan samples, while \(\langle 101\rangle\) is preferred in the X-scan sample. The controlling mechanisms of the texture, focusing on the preferential growth directions of the columnar cells and the following epitaxial growth, are discussed.

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1. Introduction
Ni—Mo alloys have been used as coating, cathode, and catalyst materials because of their high strength, good corrosion and wear resistance, and high thermal stability [1–4]. However, it is reported that the corrosion resistance and ductility is deteriorated by discontinuous long-range ordering (LRO) to form Ni_{4}Mo or Ni_{3}Mo precipitates at the grain boundary [4–6]. Thus, a single crystalline microstructure is suggested as a means to reduce the precipitate at the grain boundaries. In addition, the single crystalline microstructure is preferred for applications at elevated temperatures in order to improve creep resistance. Therefore, it is necessary to establish a strategy to control
the microstructure in Ni-based alloys to improve their mechanical properties and corrosion resistance. The prevailing manufacturing methods to obtain single crystalline microstructure or directional solidification microstructure, are the floating zone method [7,8], the Czochralski method [7,9], and the Bridgman method [7,9], which require stringent temperature control. Thus, they require high cost, and are limited in terms of accessible sizes and shapes of the product.

Recently, the additive manufacturing (AM) technology has been reported to fabricate complex-structured components at a low cost in a short time [10–12]. The control of the microstructure and texture in samples built by AM have been reported in nickel-based alloys [13–18], cobalt-based alloys [19,20], titanium alloys [21–25], steels [26,27], aluminum alloys [28,29], and so on. In some reports, the formation of single-crystalline-like microstructures was presented [13–17,19,20,24,25]. In this study, we focused on the AM of Ni–Mo alloys, for which there have been no reports to date.

Although there are many reports on the development of textures in AM samples as described above, the controlling mechanisms of the textures have not been sufficiently clarified yet, as there are numerical influencing factors from the material and build parameter aspects, such as crystallographic structure, phase transformation, power, scanning speed, and scanning strategies. In Ni–Mo alloys, the development of short-range order (SRO) is known [4–6,30–33], whose developing feature is significantly varied depending on the cooling rate [4–6,30–33]. This is one of the reasons we focused on the Ni–Mo alloy for the AM process: not only for the practical aspect but also for the fundamental aspect; i.e., to clarify the controlling factors of the microstructure, including texture depending on the cooling rate by the observation of SRO. During this study, we found that the texture developed in the Ni–Mo alloy can be varied by the scanning strategy. The mechanism of this is discussed in this paper.

The development of the texture in the AM samples, and its variation in scanning strategy [13,14,21,25] has been reported by some researchers. Recently the formation mechanism of the texture in β-Ti with body-centered cubic (bcc) structure [25] was reported, but research in the face-centered cubic (fcc) phase is still not sufficient. Based on detailed observation of the microstructure, the developing mechanism of the texture, depending on the scanning strategy, in the fcc Ni–Mo alloy is discussed.

2. Experimental procedure

For the fabrication of the AM sample, gas-atomized powder with a nominal composition of Ni-25 at.%Mo was prepared, whose diameter ranged from 10 to 45 µm with an average of 34 µm. The other detectable element contents, in mass fraction, were 0.13% Fe, 0.1% Cu, 0.26% Si, 0.05% B, and 0.05% O. The powder exhibited a spherical shape with several satellites, as shown in Fig. 1. Using this powder, 10 mm × 10 mm × 5 mm blocks were built by selective laser melting (SLM) equipment (EOS M 290) under a power of 200 W, a scanning speed of 800 mm/s, and a pitch (i.e. the distance between neighboring scanning paths) of 0.08 mm with a layer thickness of 40 µm. In this study, the build direction was defined as the z-axis, and the scanning directions, which are perpendicular to the z-axis, were defined as the x- and y-axes. Three different scanning strategies, X-scan, XY-scan, and Rot-scan, were attempted to control the texture. In the X-scan, the laser beam was scanned bidirectionally along one axis (x only). In the XY-scan and Rot-scan, the bidirectional scanning was changed with a 90° rotation and 67° rotation in each layer, respectively. The samples were cut from stainless-steel platform by electric discharge machining directly, without performing any stress relieving treatment. The built samples were cut along the xz-, yz-, and xy-planes, and the microstructures were observed by scanning electron microscopy (SEM, JEOL JSM-6500F, Japan), and transmission electron microscopy (TEM, JEOL JEM-3010, Japan). All the microstructures of the samples were observed in the as-built state, without any heat treatment. Before the observation by SEM, the specimens were etched in a solution consisting of 31% HNO3, 6% HCl, and 63% H2O with ultrasonic vibration, to see the melt-pool trace and grain boundaries clearly. Textures developed in the samples were examined by electron backscatter diffraction (EBSD) pattern analysis in the SEM at the measured step size of 3 µm at low magnification and 0.5 µm at high magnification.

3. Results

The nearly full dense sample can be obtained in all the scanning strategies in the fabrication conditions described herein. The relative densities measured by the Archimedes method for the X-scan, XY-scan, and Rot-scan sample were 99.6%, 99.8%, and 99.8%, respectively. Fig. 2(a–i) shows the crystal orientation maps analyzed by SEM-EBSD on the yz-, xz-, and xy-planes of three samples built by the scanning strategies of X-scan, XY-scan and Rot-scan, respectively. In addition, the corresponding [001], [101], and [111] pole figures along the z-axis taken from the xy-plane of the samples are displayed in Fig. 2(j, k, l). Interestingly, it was found that the crystallographic textures developed in the different scanning strategies were wholly different from one another. In the XY-scan sample, strong ⟨001⟩ alignments occurred in x-, y-, scanning and build directions (Fig. 2(b, e, h)). The corresponding ⟨001⟩ pole figure in Fig. 2(k) shows distinctly strong and sharp intensity peaks along the x-, y-, and z-axes, suggesting that a single-crystalline-like cube texture was developed. In the X-scan sample, there were the same ⟨001⟩ alignments along the x-scanning direction (Fig. 2(a)) as those in the XY-scan sample, but the preferred crystal orientation along the y-scanning and build directions were shifted from ⟨001⟩ to ⟨101⟩ (Fig. 2(d, g)). That is, a similar single-crystalline-like cube texture, but it is rotated along the x-scanning direction by 45° with respect to the one formed in the XY-scan, was developed in the X-scan. In addition, the intensity concentration of the orientations was somewhat broader in the X-scan than observed in the XY-scan sample, as shown in Fig. 2(j, k). This is because as well as the stronger concentration of ⟨101⟩ intensity, a weak concentration of ⟨001⟩ intensity was accompanied along the z-direction, as shown in Fig. 2(j). Such coexistence of concentrations of different orientations was not observed in the XY-scan sample. In the Rot-scan sample, on the other hand, a strong ⟨001⟩ alignment was developed only along the build direction (Fig. 2(c, f, i)). The ⟨001⟩ pole figure of Fig. 2(l) shows that a ring-like distribution of the ⟨100⟩ intensity with respect to the z-axis was developed in addition to the strong peak along the z-axis. This demonstrates that the ⟨001⟩ fiber texture was developed in the Rot-scan sample.

To clarify the origin for this variation in texture in different scanning strategies, detailed microstructural observations were conducted. Fig. 3(a) shows the TEM bright field image of the microstructure in the sample built by the XY-scan, and Fig. 3(b) shows the corresponding selected
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