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Excellent mechanical and corrosion properties of austenitic stainless steel with a unique crystallographic lamellar microstructure via selective laser melting

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ABSTRACT

We first developed a unique "crystallographic lamellar microstructure" (CLM), in which two differently oriented grains appear alternately, in a 316L stainless steel specimen via selective laser melting technology. The CLM was composed of major ⟨011⟩ grains and minor ⟨001⟩ grains aligned along the build direction, which stemmed from vertical and approximately ±45° inclined columnar cells formed in the central and side parts of melt-pools, respectively. The development of CLM was found to largely improve the material properties via the strengthening of the product, simultaneously showing superior corrosion resistance to commercially obtained specimens.

Crystallographic texture control has recently gained great interest in the study of additive manufacturing (AM) [1–8]. Highly texturized materials with preferential crystallographic orientations can feature mechanical anisotropies in Young's modulus [7], yield stress [2], fatigue resistance [9], creep resistance [10], etc. Therefore, crystallographic texture control, including the formation of single-crystalline textures, is believed to be an important strategy in the development of materials with superior mechanical properties through AM. The scan strategy is indicated to have an impact on texture evolution in AM, and different scan strategies lead to distinguished crystallographic orientations [5–8].

Efforts made to control crystallographic texture through AM have generated single-crystalline-like and fiber-type textures in some kinds of metallic materials [1–8]. Under a certain scan strategy, the formation of a microstructure with a single orientation is ubiquitous; however, microstructures with combinations of multiple orientations have not yet been realized, despite the fact that many materials with controlled microstructures, for example lamellar microstructures composed of different phases [11,12], show superior mechanical properties. In the present study, by utilizing selective laser melting (SLM; a powder bed fusion process), we developed a unique texture in 316L stainless steel, in which two differently oriented grains appear alternately. This unique texture is hereafter referred to as a "crystallographic lamellar microstructure" (CLM). In this paper, the detailed microstructural characteristics, mechanical properties, and corrosion resistivity—which are fundamentally expected of 316L stainless steel as a structural material—will be clarified, by comparing a specimen with CLM to that with a single-crystalline-like microstructure fabricated by SLM, as well as commercially available plate material.

Gas atomized 316L stainless steel powder was obtained from EOS GmbH (Germany) for use in the experiment. The nominal composition of the powder was 18Cr-14Ni-2.5Mo-0.03C (wt%), and the powder size was under 53 μm. SLM was conducted using an EOS M 290 3D printer by the "X-scan strategy", i.e., the laser beam was scanned bidirectionally along the *x*-axis without rotation (Supplementary Fig. 1). In this study, the laser scanning direction and build direction in SLM were defined as the *x*- and *z*-axes, respectively. By controlling the energy density, we found the optimal fabrication parameters for eliminating porosity and developing crystallographic textures: fabrication under a relatively low energy density resulted in a CLM; that under a relatively high energy density resulted in a single-crystalline-like texture. Although we focused on the unique CLM in this study, the single-crystalline-like texture formation via SLM is also novel in 316L stainless steel; therefore, 316L stainless steel plate material fabricated by standard industrial

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processes (Yakin Kawasaki, Japan) was used as an additional reference material. Products of 10 mm × 10 mm × 10 mm were fabricated for microstructure observation and corrosion tests, and those of 10 mm × 10 mm × 30 mm were fabricated for preparing tensile specimens with a gauge of 5 mm length, 1.5 mm width, and 0.8 mm thickness, as described previously [13]. To avoid unexpected heat effects from neighbor specimen melting, we ensured that there was sufficient distance between the specimens in the SLM fabrication process.

The microstructure was observed by scanning electron microscopy (SEM; JEOL JIB-4610F, Japan) following etching, and the texture development was examined by electron backscatter diffraction (EBSD) pattern analysis via SEM. Tensile tests were conducted in vacuum at room temperature with an initial strain rate of 1.67×10^{-4} s^{-1}. The loading orientation and thickness direction were set to be parallel to the *z*- and *x*-axes, respectively. To evaluate the corrosion resistance, anodic polarization measurements (linear sweep voltammetry) were performed in a 0.9 wt% NaCl aqueous solution with a potentiostat (HABF-501G, Hokuto Denko, Japan) and a function generator (HB-111, Hokuto Denko, Japan). A saturated calomel electrode (SCE) and Pt plate were used as a reference and counter electrode, respectively. The specimens were mechanically ground to #800 grit SiC abrasive paper. After immersing the specimens into the test solution at 37 °C, a gradient anodic potential was applied at a constant sweep rate of 1 mV s^{-1}. The exposed area of the specimen contacting the electrolyte was 0.35 cm^2 (6.7 mm in diameter).

The mechanical and corrosion tests were performed on three specimens in each condition ($N = 3$), and the quantitative data are given as mean ± standard deviation (SD). Comparisons between the means were statistically performed using one-way analysis of variance (ANOVA) and post hoc Tukey HSD tests (IBM SPSS Statistics 25). A value of $P < 0.05$ was considered statistically significant.

The relative densities measured by Archimedes' method were 99.6% and 99.4% for the specimens fabricated under the lower and higher energy densities, respectively, demonstrating that these optimized conditions resulted in almost fully dense specimens. Fig. 1(a, b) show inverse pole figure (IPF) maps illustrating the crystallographic texture of the specimens, observed along the *x*-, *y*-, and *z*-directions. In the specimen fabricated under higher energy density, a single-crystalline-like texture was confirmed to be developed, in which ⟨011⟩ and ⟨100⟩ were aligned nearly parallel to the build and scanning directions, respectively, as in a recent report using β-Ti with a body-centered cubic (bcc) structure [7]. On the other hand, the crystal orientation map for the specimen fabricated under lower energy density showed a characteristic lamellar pattern, despite the fact that the specimen was confirmed to be composed of a face-centered cubic (fcc) single-phase. That is, a unique CLM, in which two kinds of layers with different orientations were stacked alternately along the *y*-axis, was found to be developed.

For detailed characterization of the CLM, the misorientation angle variation along the line AB (indicated in Fig. 1(a)) is displayed in Fig. 1(c). Large misorientation angles, expressed as sharp peaks, represent

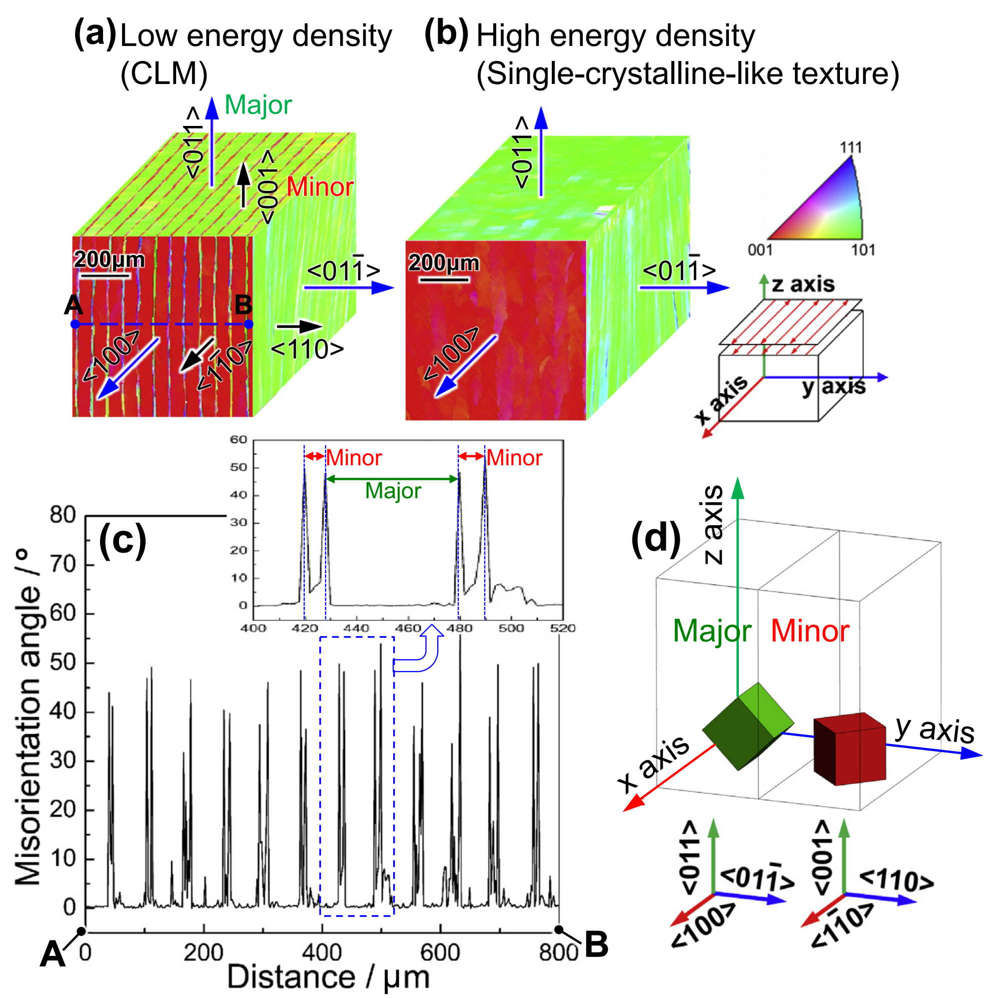

Fig. 1. Crystal orientation maps in the specimens fabricated in X-scan strategy with (a) low energy density and (b) high energy density, observed along the *x*-, *y*- and *z*-directions, respectively, taken by SEM-EBSD. (c) Misorientation angle variation along line AB in (a). (d) Schematic illustration showing the crystallographic orientation relationship between major and minor layers in the CLM formed under low energy density.