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Paper Title: High specific yield strength and superior ductility of a lightweight refractory high-entropy alloy prepared by laser additive manufacturing
Content :

Microstructural characterization and mechanical property test

The XOZ section was chosen as the observation surface for microstructure specimens. The phase structure of the alloy was analyzed using a D/MAX-2500 X-ray diffractometer (XRD). The MDI Jade software was used to analyze the XRD data. Microstructure specimens were mechanically polished using SiC emery paper and SiO_2 turbid liquid before being etched with Kroll's reagent (2 vol% HF + 12 vol% HNO_3 + 86 vol% H_2O). The microstructure was investigated using a Leica DM4000 metallurgical optical microscope (OM) and a Helios G4 CX focused ion beam scanning electron microscope (SEM) with an acceleration voltage of 15 KV and a 5 mm working distance. The element distribution of the alloys was determined using the energy-dispersive X-ray spectrometer (EDS). The electron back-scattering diffraction (EBSD) analysis was undertaken on a JEOL JSM 7900 F scanning electron microscope in 6 μm (before deformation) and 4 μm (after deformation) steps. The analysis of the related EBSD data was carried out with the TSL OIM software. The transmission electron microscope (TEM, FEI F20) was used to observe further nanostructure characterization before and after deformation, and the TEM samples were prepared by ion thinning to 50 nm thickness.

The mechanical tests were performed along the deposition Z direction. The tensile specimen measurements are presented in Fig. 2(c). The tensile test was carried out on the GNT series of microcomputer-controlled electronic universal testing machines with the servo motor driven, and a fixed strain rate of 1×10^{-3} s^{-1} was used in the experiment.

Mechanical properties and fracture behaviors

The strength and ductility of the SST sample are significantly increased relative to the as-deposited sample, as shown in Fig. 6(a). No significant yielding was observed in the as-deposited samples before fracture, with a tensile fracture strain of only 2.1% and a fracture strength of 902 MPa. The SST sample has an excellent strength-ductility match, which exhibits a tensile yield strength of 1032 ± 12 MPa and a tensile fracture strain of 25 ± 2%. Furthermore, the SST sample displays a characteristic of stress fluctuating up and down with strain in the later strain stage (10%~17% tensile strain), as shown in Fig. 6(a) black rectangle. The true stress-strain curve shows prominent strain-strengthening characteristics, as shown in Fig. 6(b), and the plastic deformation of the alloy can be divided into two stages. The strain-hardening rate curve of stage I is relatively smooth, about 1 GPa, and the jagged up-and-down behavior is observed in stage II. The SST samples have excellent comprehensive performance, as shown in Fig. 6(c). Given the density of only 5.75 $g\cdot cm^{-3}$, The SST sample has a specific yield strength of 180Mpa$\cdot g^{-1}\cdot cm^{3}$, ranking among the leading RHEAs, as shown in Fig. 6(d).

The failure fracture mode of the as-deposited and SST sample is different, as evidenced by the representative fracture morphologies and longitudinal section of fracture surfaces. The brittle fracture occurs in the as-deposited sample. The fracture exhibits a regular polyhedral morphology, with a flat fracture surface showcasing the growth and development of intergranular cracks and the secondary cracks GBs (see Fig. 7(a)), which is mainly attributed to the precipitation of brittle AlZrV phase near the GBs. The SST sample exhibits typical ductile fracture features (see Fig. 7(b)). A noticeable necking along the tensile direction can be seen, with an overall double cup cone shape and elongated grains. Numerous dimples are observed in the fracture, where some small dimples are located near the GB, indicating a strong bonding among grains. The excellent mechanical properties of SST samples may originate from their various internal plastic deformation styles, and different slip behaviors were observed in the deformed SST sample. Parallel straight and intersecting slip traces can be seen in Fig. 7(c, d). The latter usually indicates that various slip systems have operated simultaneously or alternatively. The wavy slip traces suggest the alloy experienced cross-slip during the deformation process (see Fig. 7(d)). The parallel bands (see Fig. 7(e)) and bundled slip bands (see Fig. 7(f)) may suggest the activation of twin or kink behavior[42], [43]. By contrast, the as-deposited samples have no slip deformation near the fracture, except for cracks along the GBs (see Fig. S3-S4).