Achieving The Strength-Toughness Balance Through Modified Intermediate-Temperature Aging Treatment In Laser Powder Bed Fusion Al-Ni-Cu-Fe Alloy

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Abstract : Laser powder bed fusion (LPBF) additive manufacturing, renowned for its design flexibility and rapid production, finds extensive use in the aerospace and automotive industries. LPBF-fabricated Al-Ni-Cu-Fe alloys exhibit remarkable high-temperature strength and thermal stability. However, their primary strengthening mechanism, a finely structured eutectic cell network from rapid solidification, imposes inherent limitations on ductility and toughness. While conventional T6 treatments enhance ductility, they induce grain coarsening, weakening the synergy of the distinct bimodal microstructure (fine equiaxed and columnar grains), thereby constraining the alloy's strength potential. To balance the strength-toughness of LPBF Al-Ni-Cu-Fe alloys and enhance their applicability in high-temperature, high-load aerospace, and automotive components, this study proposed a modified intermediate-temperature aging treatment specifically designed for LPBF aluminum alloys. The aging was performed at 300–500°C for 30 minutes, enabling the partial decomposition of metastable eutectic cells and contributing to precipitation while preserving the bimodal texture. This efficient, energy-saving, rapid-aging method addresses high-performance and sustainability engineering demands. The effects of aging were systematically evaluated through microstructural analysis, tensile testing, and impact testing. The results presented that 400°C provided the optimal strength-toughness balance, maintaining high yield strength (>400 MPa) and ultimate tensile strength (>500 MPa) while significantly enhancing ductility (approximately 15%) and impact resistance (increased by 35%). Aging at 400°C facilitated the controlled decomposition of the Al_9FeNi cellular structure and the precipitation of the Al_2Cu while preserving the bimodal texture stability and ensuring promising mechanical properties across varying strain rates. In contrast, 500°C corresponds to the solid-solution condition, where eutectic cells become near-complete homogenized, and the bimodal texture stability is partially compromised. The lack of sufficient driving force for precipitation formation limits the strengthening mechanism, resulting in a declining trend in strength. Nevertheless, 500°C treatment significantly enhances ductility and impact resistance, providing excellent toughness for applications requiring higher toughness, such as impact-resistant structural components. Microstructural analysis showed that partial decomposition of eutectic cells began in the fine-grained region under the aging condition of 300°C and gradually expanded into the columnar grain region as the temperature increased. Before 400°C, due to regional constraints, the ductility decreases initially and then increases. At 400°C, aging further facilitated the decomposition of eutectic cells, resulting in a uniform and finely distributed strengthening Al_9FeNi phase across both regions, achieving optimal performance balance. This study offers a practical heat treatment strategy corresponding to different application scenarios. Rapid intermediate-temperature aging demonstrates flexibility and efficiency in tailoring the performance of LPBF aluminum alloys, providing a valuable reference for future performance optimization in diverse applications.

Keywords : laser powder bed fusion (LPBF), Al-Ni-Cu-Fe alloy, bimodal microstructure, intermediate-temperature aging, cellular eutectic structure, nanoprecipitation
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