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PROCEEDINGS

High-Performance NiTi Shape Memory Alloys Fabricated by Laser Powder Bed Fusion: Orient to Functional Customization

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ABSTRACT

NiTi alloys exhibit shape memory (SME), superelasticity (SE), and elastocaloric (eCE) effects, making them well for use as functional structural components. However, their poor machinability often limits them to simple geometries like plates, rods, and tubes. Unlike Ti_6Al_4V, Ni-based superalloy, and other load-bearing materials, SMAs require a balance of geometry, mechanical, and functional properties during fabrication. Laser Powder Bed Fusion (LPBF) 3D printing technology provides a solution for manufacturing shape memory alloys (SMAs) with intricate geometries. Despite extensive knowledge of process-structure-property relationships of LPBFed NiTi alloy, successful applications have yet to be widely reported. The challenge lies in optimizing the microstructure while simultaneously forming material and geometry in 3D printing. Customizing process parameters is crucial for NiTi alloys with varying functional requirements to minimize micro-defects, achieve a suitable microstructure, enhance mechanical properties, and ensure correct functional characteristics. Therefore, our study aims to explore optimization strategies for the 3D printing process to tailor the functional customization of NiTi alloys.

Producing NiTi alloys with room-temperature superelasticity poses a significant challenge as it requires the material to be in an austenitic phase (B2) at room temperature (RT), a condition that often leads to cracking. In our study [1], we delved into the cracking mechanism using a combination of experimental and simulation methods. Our findings revealed that crack formation is influenced by a combination of thermal stress and microstructure. To achieve a stable B2 structure at RT and mitigate cracking, it is crucial to reduce the laser energy input to minimize Ni evaporation. Inadequate heat input may result in incomplete powder melting, leading to quasi-cleavage fractures under thermal stress. Conversely, excessive heat input can cause grain coarsening, increased aspect ratio, and anisotropy, all of which elevate the risk of cracking. Cracks tend to propagate along interlayers in coarse columnar grain conditions, highlighting the importance of introducing finer grains to inhibit crack propagation and facilitate the production of crack-free, room-temperature superelastic NiTi alloys. Building upon these insights, we further explored the impact of different combinations of process parameters on phase transition (PT) behavior and mechanical properties under high relative density (>99.8%) conditions [2]. Our results demonstrated that the energy input under high laser power (*LP*) conditions is lower compared to low *LP* conditions. Higher *LP*, associated with increased scanning speed (*SS*), fosters the formation of fine-grain dislocation walls central the melt pool, enhancing elastic strain energy. Moreover, lower heat inputs result in reduced Ni evaporation. Based on our crack-free fabrication approach, we recommend synergistically increasing *LP* and *SS* to produce SE NiTi alloys successfully. Leveraging these process modulation principles, we have further explored the eCE and SME functions of NiTi alloys.

Superelasticity plays a crucial role in the eCE. The modulation of eCE emphasizes the balance between grain size and Ni content, which are intertwined to the heat input and cannot be independently adjusted [3]. Therefore, while increasing laser energy input may raise the PT enthalpy, it does not significantly enhance eCE due to the weakening of superelastic properties resulting from decreased Ni content and grain coarsening. However, reducing laser energy input decreases PT enthalpy, also weakens the eCE. Simulations offer a approach to achieving a more optimal balance between Ni content and grain size. Through simulations, the strategy of synergistically increasing *LP* and *SS* might be effective. Crack-free NiTi alloy is associated with higher *SS* at high *LP*, leading to increased misorientation difference at grain boundaries and enhanced obstruction to dislocations. Based on these mechanisms, a sample with a maximum ΔT_{ad} of 24.3K has been successfully 3D printed, capable of cooling to 10°C and 6°C at ambient temperatures of 25°C and 18°C, respectively. However, the ultra-high cooling rate ($10^{6\sim8}$ K/s) resulted in a lack of reinforcing precipitates (e.g., Ni_4Ti_3) in the as-built microstructures. This leads to a limited inhibition of the dislocation motion of the microstructure and, thus, poor stability. We are currently working on a process optimization method for short-time direct aging. We propose that there is an equilibrium between matrix Ni depletion and mechanical strengthening produced by the Ni_4Ti_3 nano-particles during precipitation, which can increase the PT enthalpy and microstructural strength simultaneously.

On the other hand, we also targeted the 4D printing to investigate the shape memory properties [4]. We adopt the design concept of assigning different functional properties to different regions, to propose a partitioned-repeative scanning strategy (PRSS). Since the PT behavior of NiTi alloys is sensitive to laser parameters, it is not easy to achieve a wide, tunable range of PT behavior and mechanical properties by directly applying different parameters in different regions. This may fail to synchronize the improvement or even a decrease in mechanical properties when the PT temperature is modulated via tuning 3D printing parameters to match the desired target. Therefore, we utilize the difference in laser absorption between powder and solid materials, firstly by laser scanning to solidify alloy powder, followed by a second laser scanning to achieve staged control of PT temperature and mechanical properties. Ultimately, the NiTi alloys with a gradient change in PT temperature and balanced mechanical properties were achieved in this way. It is worth emphasizing that gradient printing is just an example, and a more flexible microstructure design is also possible using this approach. For example, it is possible to print microstructures with alternating austenite/martensite distributions to improve damping performance. Currently, we are trying to utilize this printing strategy to achieve NiTi with elastocaloric functionality of cascade microstructures via controlling the PT temperatures in different regions. This is to obtain a wide operating temperature range and high eCE performance.

KEYWORDS

Laser powder bed fusion; NiTi shape memory alloy; functional customization; elastocaloric effect; 4D printing; optimization strategies

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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