Composition Design, Property Optimization and Additive Manufacturing of High-Strength Invar Alloy

Fang Lin, Jie Wan*, Yuzeng Chen*
State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, People's Republic of China
*Correspondence: wan@nwpu.edu.cn (Jie Wan); yzchen@nwpu.edu.cn (Yuzeng Chen)

Abstract: Invar alloys, which have an ultra-low coefficient of thermal expansion (CTE), are widely used in precision instrumentations. However, their relatively low strength poor machinability limits their application in wider fields. Introducing diffused carbide particles into the Fe-Ni-Co Invar alloy, which has a negative CTE, can strengthen the alloy and regulate its CTE value. The high-strength Fe-Ni-Co Invar alloy was designed and fabricated via selective laser melting (SLM). Mechanical properties and CTE for designed alloy were measured using electronic universal tensile testing machine and thermal expansion analyzer, respectively. Results showed that the designed alloy demonstrates a low CTE and significantly improved strength compared with the traditional Invar alloys. Strengthening mechanism is being investigated utilizing SEM and TEM.

Keywords: Invar alloys; Selective laser melting; Strengthening mechanism

1 Introduction

Inva36 is widely used in precision components such as space telescopes, reference scales and arms of precision balances for its low CTE under Curie temperature[1]. However, its low yield strength (300MPa) limits its application in wider fields[2]. The excellent plasticity of Invar36 also make it difficult and inefficient to form complex parts by conventional manufacturing methods.

Selective laser melting (SLM) can realize the near-net forming of metal parts, which provides a new favorable way for the efficient forming of Invar36 parts. The process parameters, mechanical properties and CTE of Invar36 fabricated via SLM have been deeply studied. It was reported that the as-built Invar36 samples show a high relative density when the laser energy density is between 90-110J/mm^3[3, 4]. SLM-Invar36 shows a higher yield strength (YS, 300-400MPa) than conventionally manufactured specimens [4, 5]. While the CTE of SLM-Invar36 is lower than that of conventionally manufactured counterpart[6].

Conventionally, carbides were introduced into Invar36 to enhance its YS and ultimate tensile strength (UTS)[7, 8]. But the addition of these elements causes an increase of the CTE. It is reported that replacing Ni with Co in Invar36 can make its CTE lower, showing obvious negative expansion [9]. For high-precision parts, neither expansion nor negative expansion is expected. Therefore, the simultaneous introduction of Co and strengthening elements into Invar36 is expected to improve the strength while maintaining its low CTE.

In this work, Fe-Ni-Co-V Invar alloy was designed, with V and C elements added and with 4 wt.% Co instead of Ni element in Invar36. The dense samples were obtained by SLM. The thermal expansion and mechanical properties of the as-built Fe-Ni-Co-V Invar were studied. The effects of heat treatment on the properties of the designed alloy were also investigated.

2 Experimental procedure

Nitrogen atomized Fe-Ni-Co-V Invar powder were used in this study. Table 1 presents the composition of the alloy powder. The specimens were fabricated using a BLT-S320. In this study a laser power of 300W, a scanning speed of 700mm/s, a hatch spacing of 0.15mm and a powder layer thickness of 30μm were used to fabricate specimens. In order to obtain nano-carbides, some specimens were aged at 650℃ for 3h.

Table 1 Composition of Fe-Ni-Co-V Invar powders (wt.%).

Elements	Ni	Co	V	C	Fe
Fe-Ni-Co-V Invar	32.10	3.47	1.80	0.08	Bal.

3 Result and discussion

Microstructure

Fig.1(a) and (b) display the metallography of as-built and aging treatment (AT) Fe-Ni-Co-V Invar, respectively. It can be observed that the angle between scanning tracks in different layers was about 67°, consistent with the scanning strategy (Fig. 1(a)). After aging treatment, the grains arranged along the scanning tracks in the specimens (Fig. 1(b)). There is no obvious change in grains size after aging treatment (30μm on average). It is obvious in Fig. 1(c) that the as-built sample is full of cellular structures with a high density of dislocations accumulated along the cell boundaries. Diffused carbide particles can be observed in the specimen after aging treatment, with dislocation cells existing (Fig. 1(d)).

Fig. 2 shows tensile stress-strain curves of as-built and AT Fe-Ni-Co-V Invar specimens. Obviously, AT can improve the strength of the alloy: as-built specimen possessed the YS of 495 MPa, while AT specimens demonstrated a higher value of 594MPa.

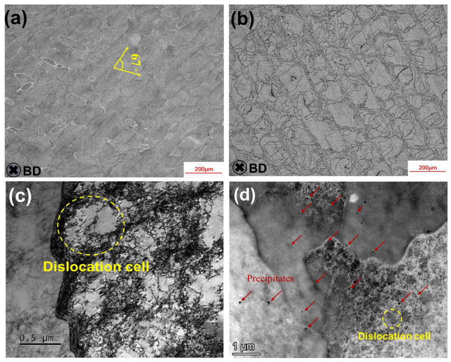

Fig. 1 OM micrographs of (a) As-built Fe-Ni-Co-V Invar; (b) AT Fe-Ni-Co-V Invar and TEM micrographs of (c) As-built Fe-Ni-Co-V Invar; (d) AT Fe-Ni-Co-V Invar.

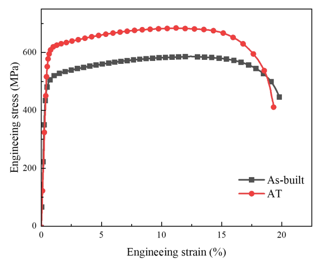

Fig. 2 Tensile engineering stress-strain curves of As-built and AT Fe-Ni-Co-V Invar specimens.

Tensile behavior

The YS of as-built Fe-Ni-Co-V Invar is significantly higher than that of Invar36 fabricated via SLM, which may be due to the solid solution strengthening caused by the addition of V and C. After AT, the strength is further enhanced because of the precipitation of carbide.

Thermal expansion properties

Fig. 3(a) displays the change in length of as-built and AT specimens as a function of temperature. AT has no obvious effect on the CTE of Fe-Ni-Co-V Invar fabricated via SLM. This may due to the release of residual stress and precipitation of carbide. Fig. 3(b) shows the absolute values of CTE (|CTE|) of different alloys at different temperature ranges. In the low temperature range (30-100℃), Fe-Ni-Co-V Invar shows a low |CTE|, which is similar to Invar36. While Invar36 has a lower |CTE| at the high temperature range (30-200℃).

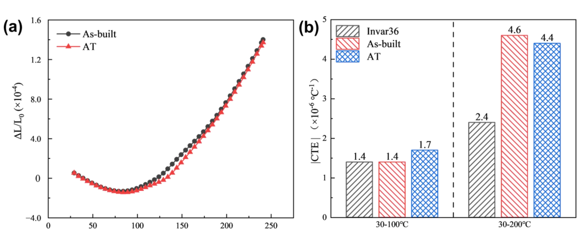

Fig. 3 (a) Thermal expansion curves of As-built and AT Fe-Ni-Co-V Invar; (b) absolute value in different temperature ranges of Invar36, As-built and AT Fe-Ni-Co-V Invar.

4 Conclusion

The as-built Fe-Ni-Co-V Invar has significantly higher strength than Invar36, and aging treatment can further enhance its strength without affecting its thermal expansion properties. Fe-Ni-Co-V Invar demonstrates a low absolute value of CTE at low temperature.

5 Acknowledgments

This work was supported by the National Key Research and Development Program of China (Nos. 2022YFB3404203) and the Natural Science Basic Research Program of Shaanxi Province, China (No. 2023-JC-QN0421).

References

[1] M. Yakout, A. Cadamuro, M.A. Elbestawi, S.C. Veldhuis, The selection of process parameters in additive manufacturing for aerospace alloys, The International Journal of Advanced Manufacturing Technology 92(5-8) (2017) 2081-2098.

[2] H. Liu, Z. Sun, G. Wang, X. Sun, J. Li, F. Xue, H. Peng, Y. Zhang, Effect of aging on microstructures and properties of Mo-alloyed Fe–36Ni invar alloy, Materials Science and Engineering: A 654 (2016) 107-112.

[3] M. Yakout, M.A. Elbestawi, S.C. Veldhuis, Density and mechanical properties in selective laser melting of Invar 36 and stainless steel 316L, Journal of Materials Processing Technology 266 (2019) 397-420.

[4] K. Wei, Q. Yang, B. Ling, X. Yang, H. Xie, Z. Qu, D. Fang, Mechanical properties of Invar 36 alloy additively manufactured by selective laser melting, Materials Science and Engineering: A 772 (2020).

[5] Q. Yang, S. Yang, S. Ma, J. Zhou, Y. Zhou, R. Huang, K. Wei, Z. Qu, X. Yang, In-situ X-ray computed tomography tensile tests and analysis of damage mechanism and mechanical properties in laser powder bed fused Invar 36 alloy, Journal of Materials Science & Technology 175 (2024) 29-46.

[6] N.J. Harrison, I. Todd, K. Mumtaz, Thermal expansion coefficients in Invar processed by selective laser melting, J Mater Sci 52(17) (2017) 10517-10525.

[7] K. Nakama, K. Sugita, Y. Shirai, Effect of MC Type Carbides on Age Hardness and Thermal Expansion of Fe–36 wt%Ni–0.2 wt%C Alloy, Metallography, Microstructure, and Analysis 2(6) (2013) 383-387.

[8] Q.S. Sui, J.X. Li, Y.Z. Zhai, Z.H. Sun, Y.F. Wu, H.T. Zhao, J.H. Feng, M.C. Sun, C.L. Yang, B.A. Chen, H.F. Peng, Effect of alloying with V and Ti on microstructures and properties in Fe–Ni–Mo–C invar alloys, Materialia 8 (2019).

[9] X. Rao, Y. Ru, F. Guo, Y. Ren, L. Cui, K. Yu, Abnormal strain evolution of austenite upon martensitic transformation in FeNiCo alloy with invar effect: An in situ study, Scripta Materialia 220 (2022).