

Microstructure and mechanical properties of additively manufactured Invar alloys: A critical review

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Abstract: Invar alloy, as a typical low-expansion alloy material, has broad application prospects in aerospace and precision instrumentation fields. However, with the increasing demands for the comprehensive performance and structural precision of Invar alloy components in advanced equipment supports, the limitations of traditional manufacturing methods for Invar alloys have become increasingly obvious. Additive manufacturing technology demonstrates significant advantages in the near-net shaping of complex components and the optimization of alloy properties, offering potential solutions to the difficulties of low strength, poor machinability, and changeable temperature range associated with Invar alloys. This review focuses on analyzing and summarizing relevant research findings regarding the optimization of microstructure, performance, and applications of Invar alloys through additive manufacturing technology. Additionally, it consolidates recent exploratory studies on the engineering applications of additively manufactured Invar alloys. Finally, this paper anticipates key challenges that need to be addressed in future research on the additive manufacturing of Invar alloys.

Keywords: Invar alloy; additive manufacturing; mechanical properties; thermal expansion properties; process parameter optimization

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1 Introduction

Most materials in nature exhibit thermal expansion properties. If their length or volume increases with rising temperature, this phenomenon is defined as positive thermal expansion (PTE). Conversely, there are certain materials whose length and volume remain unchanged over a specific temperature range or even decrease with increasing temperature, which are referred to zero thermal expansion (ZTE) and negative thermal expansion (NTE) materials^[1]. Most common materials belong to the category of PTE materials, which means that when the operating temperature changes, the

dimensions of the workpiece may vary significantly, necessitating consideration of deformation-related failures. Materials with low absolute values of coefficient of thermal expansion (CTE) including ZTE and NTE materials are generally called low expansion materials, which can better meet engineering requirements in the field of a wide temperature range and high precision. Among the various low-expansion materials, metals offer advantages such as high strength, good electrical/thermal conductivity, and high ductility, making them irreplaceable in modern industry. Invar alloy is the first low-thermal-expansion metal to be discovered. It features tunable thermal expansion properties and works over a wide temperature range from approximately −196 °C to 230 °C^[2].

As a typical low-expansion metal, Invar alloy's CTE can reach below 2.0 ppm·°C^{−1}, effectively addressing deformation issues in environments with temperature fluctuations, particularly in extreme temperature conditions, thus maintaining the dimensional stability of

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functional structures. Consequently, it has been widely applied in various engineering fields^[3-7], including space astronomical observation, integrated circuits, precision instruments, satellite structures, optics, and gas transportation.

Unlike most special steels, Invar alloys generally exhibit low strength and hardness, with tensile strength typically below 500 MPa, which is primarily due to the ferromagnetic elements such as Fe, Ni, and Co. Additionally, the alloy is predominantly maintained in an austenitic structure, and is easy to stick to the tool, which reduces the accuracy and efficiency of traditional machining. Consequently, Invar alloys commonly face issues related to low strength and hardness and poor machinability^[8]. Since the 20th century, the manufacturing method for Invar alloys is mainly forging. However, this approach has several shortcomings: (1) The production of complex components, such as thin-walled parts, cavities, and porous structures, is difficult, making it hard to achieve the great precision; (2) Precise control of mechanical properties of components is challenging, and the necessary subsequent heat treatment process is complex. To address these shortcomings and better meet production demands across various fields, exploring manufacturing processes beyond forging has become a new direction in Invar alloy research.

Additive manufacturing (AM), also known as 3D printing, is an advanced manufacturing technology that utilizes computer-aided design (CAD) data to fabricate parts layer by layer^[9]. This technology eliminates the need for manufacturing molds and avoids the waste of materials in material reduction manufacturing, making it suitable for the high degree of structural design freedom and rapid production of complex-shaped components^[10]. Since the introduction of stereolithography and powder bed fusion technologies in the 1980s, AM has evolved into widely used techniques, such as laser powder bed fusion and electron beam melting. Compared to traditional processes, additive manufacturing offers advantages such as short production cycles, high automation, design flexibility, the ability to directly manufacture complex structures, and the elimination of mold requirements, leading to its widespread adoption in metal manufacturing. Additive manufacturing has not only achieved remarkable advancements in technical aspects, such as increased printing speed, high precision, and a wider variety of available materials, but has also facilitated its extensive applications in fields including aerospace, rail transportation, energy, electronics, and biomedicine. The emergence and extensive application of this technology provide new solutions to the problems caused by traditional processing and have made it a focal point of research in the field of Invar alloys. The primary objective of this review is to systematically synthesize current research advancements in the additive manufacturing of Invar alloys, encompassing microstructure, performance, and applications. In addition, the emerging application domains of additive manufacturing Invar components are comprehensively analyzed. The paper concludes with a critical assessment of current technical challenges and proposes a roadmap for future

development, highlighting critical gaps in process-structure-property relationships.

2 Microstructure of Invar alloys prepared by different additive manufacturing methods

Invar alloy is available in various grades, such as 4J36, 4J32, and 4J29. The most fundamental grade is designated as 4J36, which is widely used due to its excellent Invar effect and certain mechanical properties^[11]. Its elemental composition is presented in Table 1^[12]. Super Invar alloy (4J32) was discovered by Japanese Masumoto^[13] in 1927 on the basis of 4J36 Invar alloy. Its microstructure stability at low temperature is slightly lower than 4J36 Invar alloy, but it shows a lower CTE below the Curie temperature, with $\alpha_{20-100\text{ }^{\circ}\text{C}}=0.9\times10^{-6}\text{ }^{\circ}\text{C}^{-1}$, which is among the commonly used brands of Invar alloy^[14]. Kovar alloy (4J29)^[15] exhibits matched thermal expansion with some high borosilicate glass and high Al_2O_3 ceramics in a wide temperature range, and possesses high thermal stability. It is often used as the main sealing structure of vacuum devices. In addition, other Invar alloys include stainless Invar alloy^[16], $\text{FeNi}_{33}\text{Co}_{14}$ (4J33), and $\text{FeNi}_{29}\text{Co}_{20}$ (4J34)^[17].

The basic difference between different grades of Invar alloys is the proportion of Ni element. The change of Ni content greatly affects the coefficient of thermal expansion of Invar alloy due to the joint action between the magnetostrictive effect of austenitic structures and the general thermal expansion/contraction effect of objects^[18], as shown in Fig. 1^[19]. When the magnetic elements Fe and Ni meet a certain proportion, especially the proportion of Ni is in the range of 32%–38%, the alloy structure is dominated by austenite.

Current research on additive manufacturing of Invar alloy primarily focuses on laser powder bed fusion (L-PBF), directed energy deposition (DED), and wire arc additive

Table 1: Chemical composition of 4J36 Invar alloy (wt.%)^[12]

Grade	Fe	Ni	Mn	Si	C	P	S
4J36	Bal.	35–37	0.2–0.6	≤0.3	≤0.05	≤0.02	≤0.02

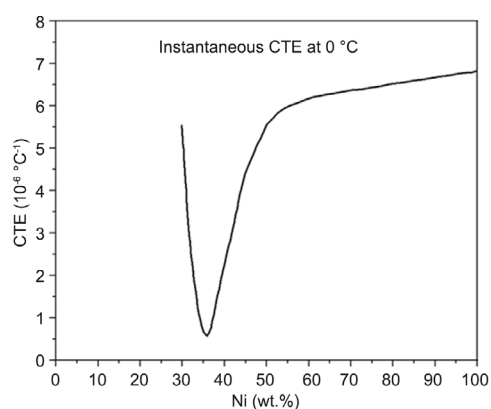


Fig. 1: Influence of Ni ratio on thermal expansion coefficient of Invar alloys at 0 °C^[19]

manufacturing (WAAM)^[20, 21]. Consequently, this paper provides a comprehensive review and comparative analysis of the Invar alloys prepared by L-PBF, DED, and WAAM.

2.1 Microstructure of Invar alloys manufactured by L-PBF process

2.1.1 Microstructure characteristics

The microstructure of 4J36 Invar alloy prepared by L-PBF is shown in Fig. 2^[22], including thick columnar grains spanning multiple melt pools in *XOZ* cross-section. The characteristic microstructure can be divided into three categories^[23-25, 27-29]: columnar subgrains growing vertically inward from the

melt pool boundary [Fig. 2(c)], fusion lines located at the edge of the melt pool [Fig. 2(d)], and cell subgrains located primarily in the remelting zone [Fig. 2(e)]. According to the theory of compositional subcooling, the grain morphology is determined by the temperature gradient (G) and crystallization rate (R). As shown in Fig. 3(a), the reduction of G/R ratio results in the transformation of planar subgrains to cellular crystals and subsequently to columnar crystals. In a single melt pool, as shown in Fig. 3(b), solidification begins at the bottom of the melt pool. The temperature of the melt pool is transferred to the base through the fusion line, resulting in the highest temperature gradient at the liquid-solid interface

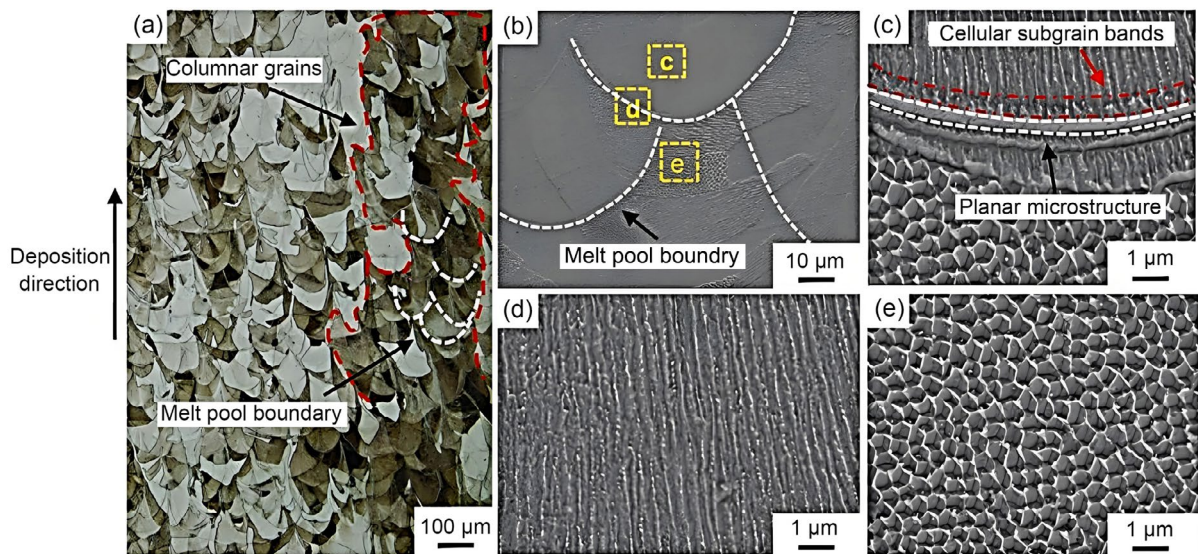


Fig. 2: Characteristic microstructures of 4J36 Invar alloys produced by L-PBF: (a) OM and (b) SEM micrographs of cross-sections; (c) columnar subgrains; (d) planar grains; (e) cellular subgrains^[22]

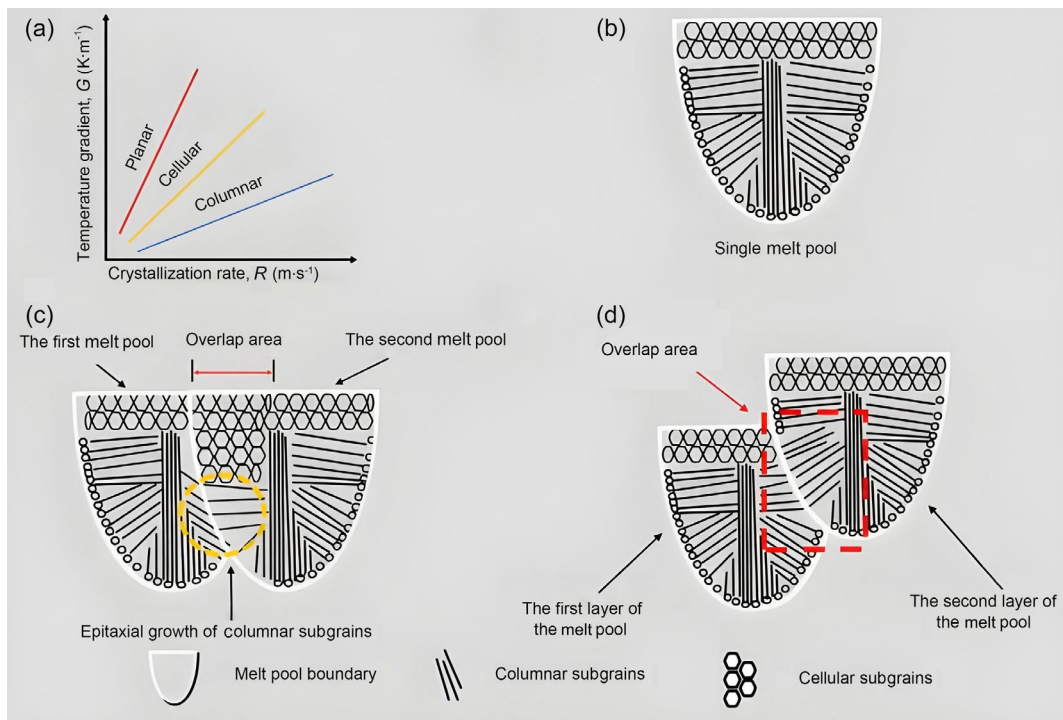


Fig. 3: Formation mechanism of different subgrains: (a) combined effect of G and R on solidification microstructure; (b) subgrain structure evolution in a single melt pool; (c) subgrain structure evolution in the adjacent melt pool; (d) subgrain structure evolution in the upper and lower adjacent melt pools^[25]

and the lowest crystallization rate. As a result, fine cellular crystals form in the bottom region of the melt pool. The G decreases as the solidification process progresses, prompting the growth of subgrains along the planar grains. Furthermore, the combination of temperature gradient and solidification rate on the top surface of the melt pool can induce the formation of cellular subgrains. When adjacent melt pools overlap in the same layer, local remelting occurs in the overlapping area, and columnar subgrains rely on the first solidified grain to undergo epitaxial growth [Fig. 3(c)]. When the upper and lower layers of the melt pool overlap, columnar crystals grow epitaxially across layers along the deposition direction, ultimately forming continuous long columnar crystals that penetrate multiple layers [Fig. 3(d)]. The microstructure characteristics of 4J36 Invar alloys manufactured by L-PBF are similar to those of typical metals such as 316L^[26].

Qiu et al.^[8] found that the L-PBF Invar alloy is mainly composed of γ phase (about 90% area fraction), with an α precipitated phase (about 5% area fraction), as shown in Fig. 4. However, in the report of the 4J36 Invar, only a single austenite phase was found by XRD^[27], as shown in Fig. 5. This may be due to the limitation of detection accuracy, which cannot detect only 5% of α -Fe. Therefore, the L-PBF 4J36 Invar alloy is primary composed of FCC γ -FeNi phase and a very small amount of α -Fe phase.

In addition to the above matrix structure, second phase particles are introduced into Invar alloy to improve the mechanical properties. For Invar alloy, solid solution strengthening is mainly achieved through the action of Ni and other additive elements, which has limited effect^[28, 29]. Second-phase strengthening in Invar alloys is a powerful means of enhancing Invar alloys in many additive manufacturing

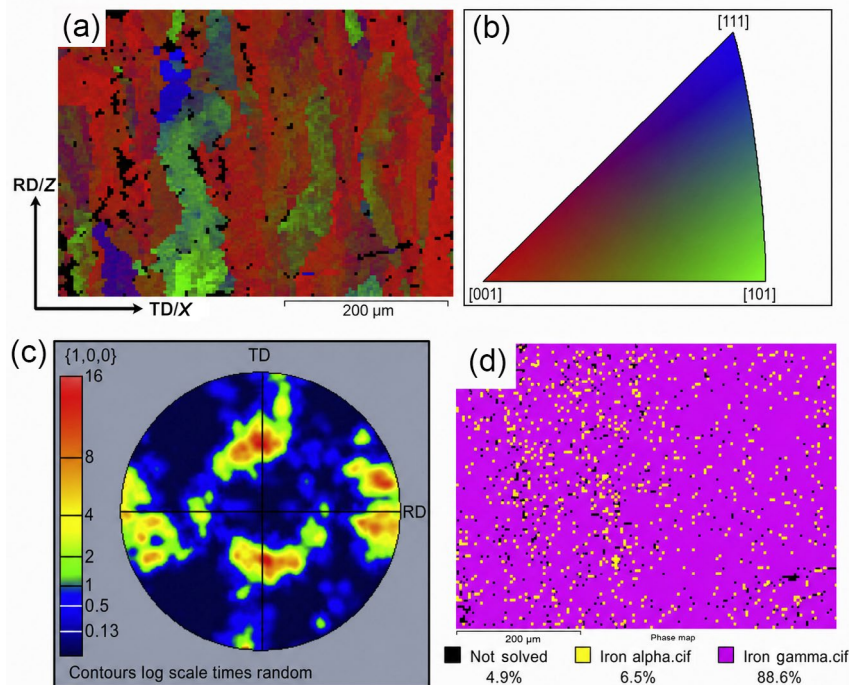


Fig. 4: EBSD image showing the L-PBFed microstructure (a), inverse pole figure (b) and pole figure (c) obtained from EBSD map (d) showing the distribution and area fraction of different phases. The building direction was along Z direction^[8]

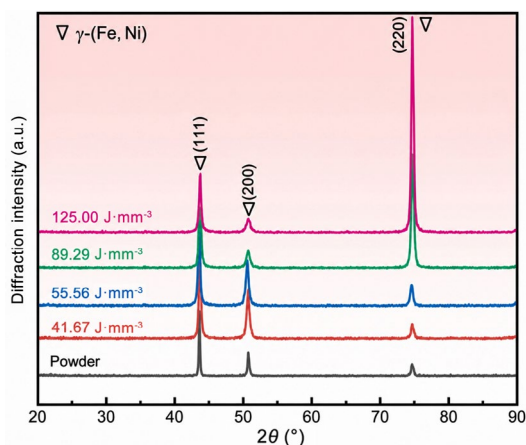


Fig. 5: XRD patterns of 4J36 Invar alloy manufactured by L-PBF^[27]

studies. Liu et al.^[30] used a lower dissolution temperature of 1,050 °C to treat Mo strengthened Invar alloy. Due to the incomplete dissolution of primary carbides, the precipitation strengthening effect was not ideal. Sui et al.^[31] enhanced the maximum tensile strength to 940 MPa by introducing strong carbides or carbon nitrogen forming elements V, Ti into Mo-alloyed Invar alloy. Qiu et al.^[32] incorporated TiAl intermetallic compound (Ti-48Al-2Cr-2Nb) powder into 4J36, subsequently fabricating via L-PBF a novel Invar alloy with notably enhanced mechanical properties. As shown in Fig. 6, the added TiAl compound induced: (i) nanoscale Al₂O₃ and γ -TiAl precipitates within the austenitic matrix, and (ii) elemental segregation of Ti/Al coupled with precipitate enrichment of TiNi compounds. The former effectively impedes dislocation motion, constituting the primary

strengthening mechanism, while the latter introduces increased crack initiation sites that degrade ductility, with concurrent Ni depletion adversely affecting the low thermal expansion characteristics. Overall, the developed alloy demonstrates

significant improvement of mechanical properties while maintaining satisfactory low thermal expansion and ductility, showing promising potential for structural-functional applications.

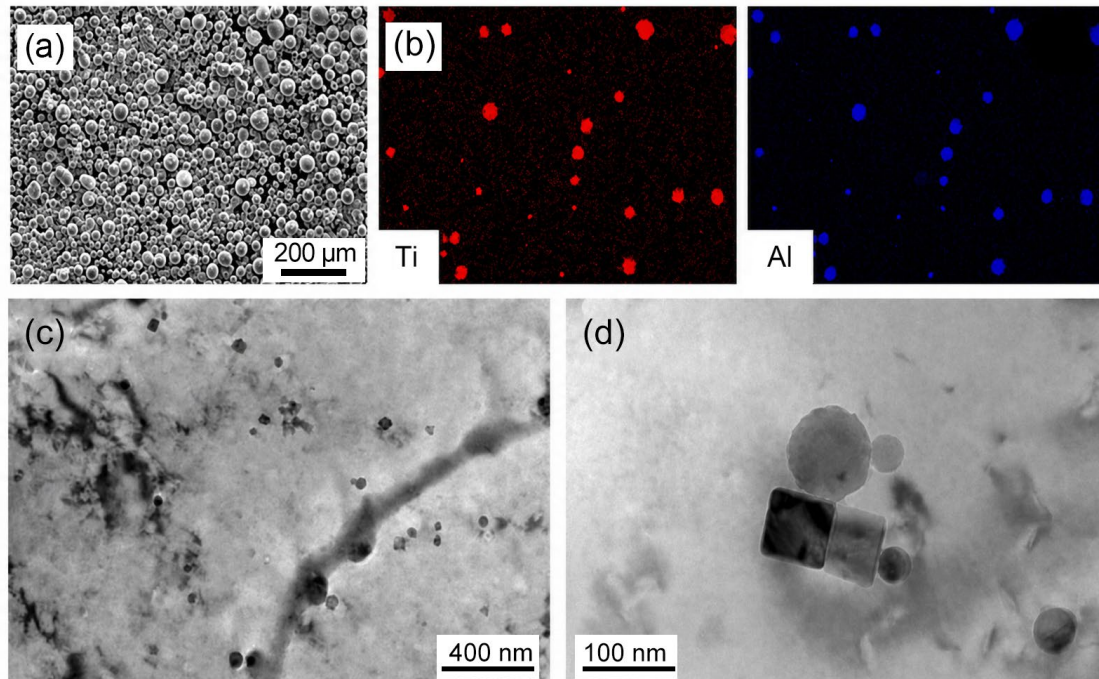


Fig. 6: SEM and EDX analysis of TiAl powder mixed with Invar36 powder (a)–(b), second phase distribution and morphology of 4J36 Invar alloy (c)–(d)^[32]

2.1.2 Defects

Owing to the inherent weldability of Invar alloys, additive manufacturing Invar components under optimized parameters seldom exhibit critical macro-defects (e.g., cracks), with porosity remaining the primary intrinsic imperfection. The densification and defects of Invar alloy can be effectively controlled by adjusting the additive manufacturing process parameters. For example, insufficient laser power will lead to insufficient bonding between powders, forming porosity and lack of fusion defects. However, if the laser power is too high, the molten pool will boil violently and eject molten metal and powder. At the same time, the protective gas will be drawn into the molten pool, forming spherical holes, keyholes, and other defects^[33, 34]. Wei et al.^[35] revealed the effects of L-PBF process parameters (especially volume energy density, E_v) on defect types of 4J36 Invar alloy, as shown in Fig. 7. At the energy density of $23.5 \text{ J} \cdot \text{mm}^{-3}$, the surface morphologies showed obvious unmelted defects. With the energy density increasing, the unfused defects were improved, and the melting boundary could be clearly observed. When the energy density was increased to $99.2 \text{ J} \cdot \text{mm}^{-3}$, the dense microstructure with obvious melt boundary was obtained. As the energy continued to increase, some keyholes could be observed. Zhang et al.^[36] also obtained similar results, finding that the surface quality is not ideal when the laser power is too low or too high. Therefore, it is important to select appropriate printing process parameters for Invar alloys.

2.2 Microstructure of Invar alloys manufactured by DED

2.2.1 Microstructure characteristics

Different additive manufacturing processes will also affect the microstructure of Invar alloy. Li et al.^[37] revealed the microstructure evolution of cellular, columnar, and equiaxial crystals during the directional energy multi-layer deposition process in 4J36 Invar alloy. In the deposition process, the temperature gradient is the core factor that determines the grain morphology. The temperature gradient G at the liquid-solid interface is the largest, and columnar crystals are preferentially formed. As the solidification process progresses, the temperature gradient decreases gradually, forming an alternate arrangement of columnar and cellular structures (Fig. 8). The center area at the top of the molten pool is the final solidification site with the smallest temperature gradient, resulting in the formation of equiaxed crystals. Zhan et al.^[38] studied the process of the columnar to equiaxial transition during laser melting deposition of Invar alloy by modeling and simulation. The results showed that the bottom of the molten pool was filled by the epitaxial growth of columnar grains, and the orientation of the columnar grains was consistent with the direction of the maximum temperature gradient. The top of the molten pool was occupied by equiaxed grains. At the same time, Zhan et al.^[29, 39] also observed the microstructure of DED components of Invar alloy, and its microstructure characteristics are similar to those reported by Li et al.^[37]. Its

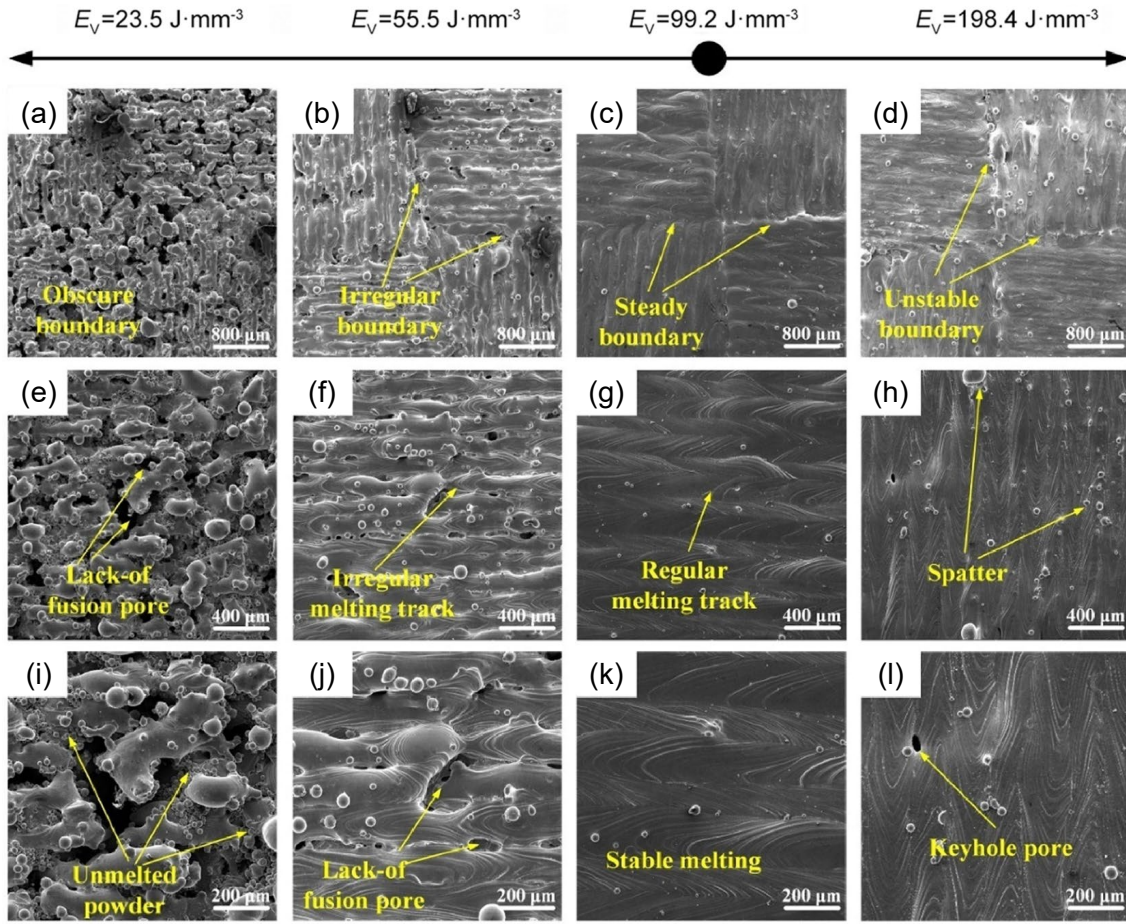


Fig. 7: Surface morphologies of Invar alloy printed with different laser energy densities (a-l)^[35]

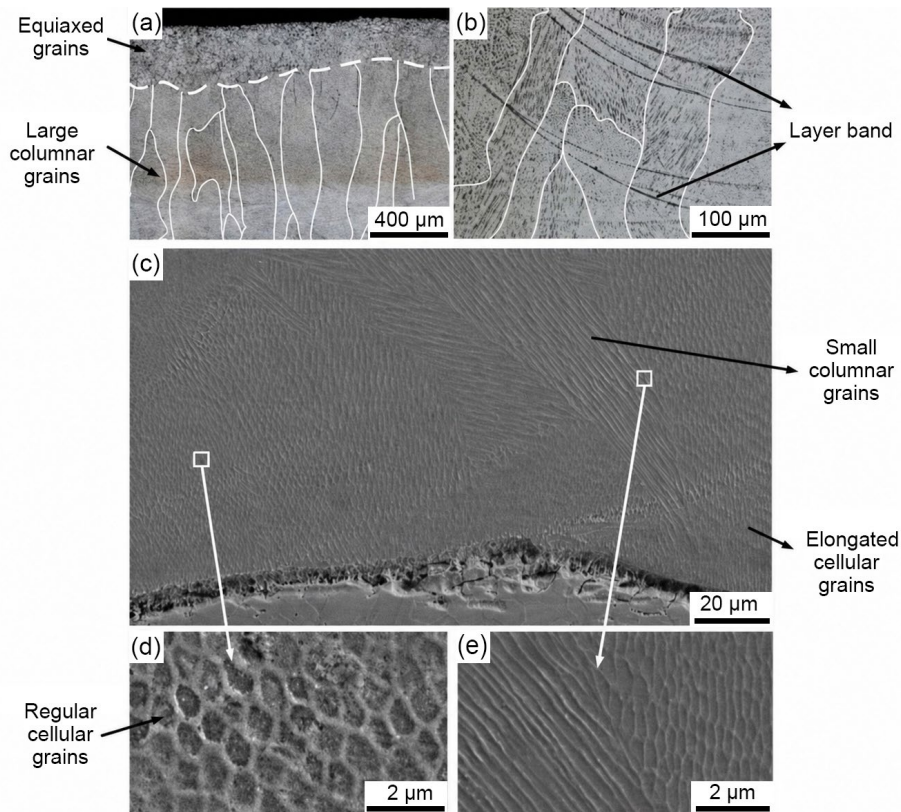


Fig. 8: OM micrographs of top and middle of as-deposited sample showing equiaxed and large columnar grains (a), OM micrographs of middle part of sample showing cellular and columnar grains traverse many layers (b), SEM micrographs of bottom of sample showing regular and elongated cellular grains and small columnar grains (c) with microstructure details showing in (d, e)^[37]

microstructure is also similar to L-PBF, which is caused by the high cooling rate generated by additive manufacturing. But the difference between DED and L-PBF is that the energy input generated by DED is larger. L-PBF usually has an input power below 500 W, but the energy used in DED can be several thousand watts, which leads to coarser grain size in the samples.

To reveal the phase constitution of the deposited 4J36 Invar alloy, Zhan et al.^[29] conducted XRD and energy dispersion spectrometry (EDS), as shown in Fig. 9. The diffraction peak of the deposited sample is composed of austenitic phase with nickel dissolved in γ -Fe [Fig. 9(a)]. The main strong diffraction peaks are (1 1 1), (2 0 0), (2 2 0), (3 1 1), (2 2 2). It is important to note that the intermetallic compounds and nanoscale carbides are not found in the XRD profile due to their extremely small number and size. The microstructure of the deposited sample is face-centered cubic. Figure 9(b) shows the EDS point results, indicating the uniform distribution of each element. Similar findings have also been reported in other studies^[38, 39]. In summary, the microstructure of Invar alloy manufactured by DED-powder is mainly composed of γ -Fe.

2.2.2 Defects

The defects of Invar alloy manufactured by DED-powder are affected by many factors. During laser cladding, the application of gas protection helps to alleviate porosity (pore) defects in the deposited layer^[40]. The porosity is a common defect in the deposition process. The porosity can be divided into bubble defect and fusion defect according to the formation reasons. The morphology of the two kinds of porosity in the Invar alloy component is shown in Fig. 10^[29]. The bubble pores are usually regular spherical or elliptic, with diameters

up to tens of microns. The fusion-defect pores usually show irregular shapes in the micron scale. Zhan et al.^[29] used energy spectrometer to characterize the chemical components of the matrix and different pore interfaces (Fig. 11). The elemental composition of the matrix and the fusion defect pores is similar, and their chemical composition is consistent with that of Invar alloy. The content of Mn, Fe, and Ni elements of the matrix and the pore interface of the bubble is obviously different, which indicates that some elements burn and vaporize during the cladding process, thus forming porosity defects.

Due to the inherent low thermal expansion property of Invar alloy, it shows lower delamination and cold cracking tendency during the laser additive manufacturing process. Sood et al.^[41] studied the microstructure and thermal expansion properties of Invar36 alloy under different heat input densities, and found that the increase of heat input density led to the coarsening of microstructure, which was more prone to macro cracks. Tan et al.^[42] studied the mechanism of crack formation in laser additive manufacturing of Invar alloy. As shown in Fig. 12, the sample prepared at powder feed rate of $6.7 \text{ g} \cdot \text{min}^{-1}$ and scanning rate of $300 \text{ mm} \cdot \text{min}^{-1}$ exhibits a large number of cracks and pores. The propagation direction of the cracks is parallel to the deposition direction, and the cracks are mainly distributed along the grain boundaries with typical characteristics of intergranular cracking. In addition, the orientations of the dendritic structures on both sides of the crack are significantly different, as shown in Fig. 12(b). It can also be seen in Fig. 12(c) that there are continuously distributed pores at the grain boundary, and the dendrite orientations on both sides of the pores are obviously different, which may be the source of the cracks.

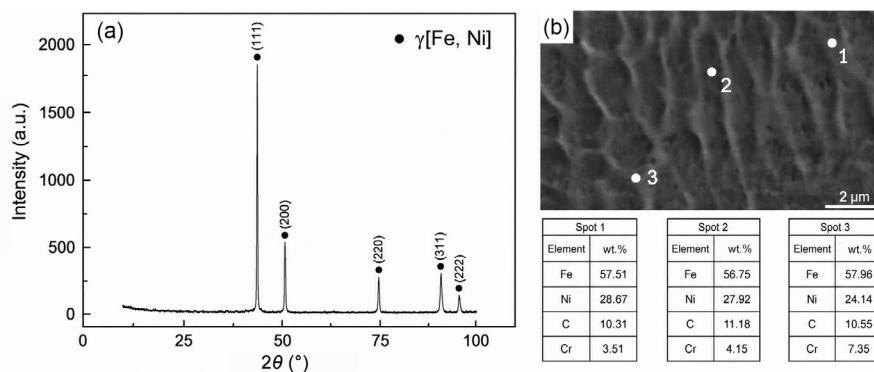


Fig. 9: XRD profile (a) and EDS (b) of deposited 4J36 Invar alloy^[29]

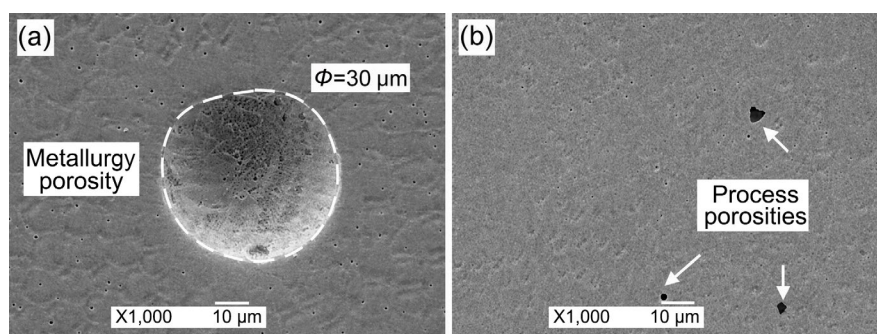


Fig. 10: Porosities in Invar alloy coatings: (a) bubble porosity; (b) fusion lack porosity^[29]

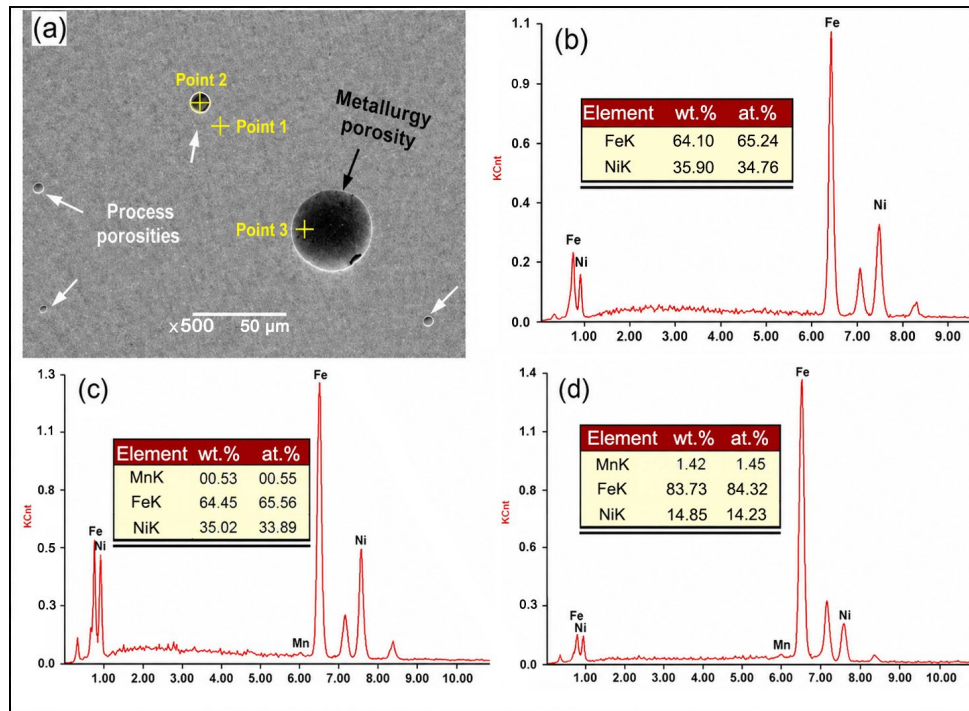


Fig. 11: EDS results of porosities: (a) local enlargement; (b-d) EDS results detected at marked Point 1 (b), Point 2 (c), and Point 3 (d)^[29]

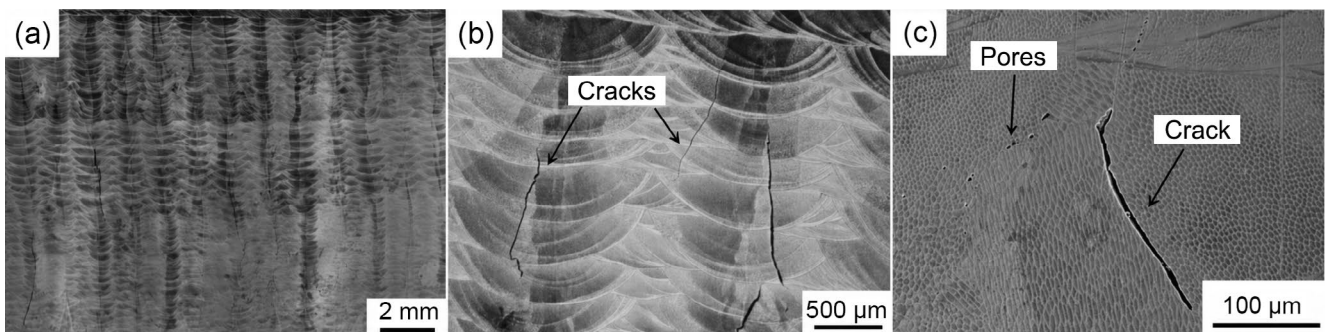


Fig. 12: Cracks in microstructure at a scanning speed of $300 \text{ mm} \cdot \text{min}^{-1}$: (a) OM macrostructure; (b) high-magnification image of crack morphology; (c) SEM image of crack^[46]

2.3 Invar alloys manufactured by WAAM

The mainstream DED-wire technology uses an arc as the energy source, known as WAAM^[43-45]. The microstructure and properties of Invar alloys prepared under different conditions are also different. Aldalur et al.^[46] compared the microstructure and properties of Invar36 alloy under different processes, and found that its microstructure characteristics were related to the process heat input characteristics. WAAM process has higher heat input and slower cooling rate, resulting in coarse grains and obvious interlayer remelting. Jiao et al.^[47] explored the microstructures, mechanical properties, and the CTE of an Invar alloy fabricated by WAAM. The microstructures of the as-deposited and heat-treated samples consist of columnar γ grains decorated by primary phase and dispersoids. The precipitated phases were identified as (Nb, Ti)C (0.5–1 μm) and NbC (30–500 nm). Antonia et al.^[48] observed the elemental influence of Ti, Zr, and Hf on 4J36 Invar alloy by adding these trace elements into the Invar alloy wire, as shown in Fig. 13. The test results show that the three trace elements cannot

significantly change the microstructure and grain size of 4J36 Invar alloy, and only induces differences in hardness.

3 Performance of Invar alloys

3.1 Mechanical properties

The mechanical properties of Invar alloy are different under different preparation processes. Table 2 shows the ultimate tensile strength and elongation of 4J36 Invar prepared by traditional method, L-PBF, DED, and WAAM. It can be seen from Table 2, additive manufacturing of Invar alloy compared with forged Invar alloy has a strong competitiveness, basically can reach the ASTM prescribed forgings level. The maximum ultimate tensile strength has reached 530–550 MPa. At present, relevant studies mainly based on 4J36 Invar, there are few reports on other Invar compositions. Expanding the research on additive manufacturing of other Invar alloy grades will be one of the key future research directions.

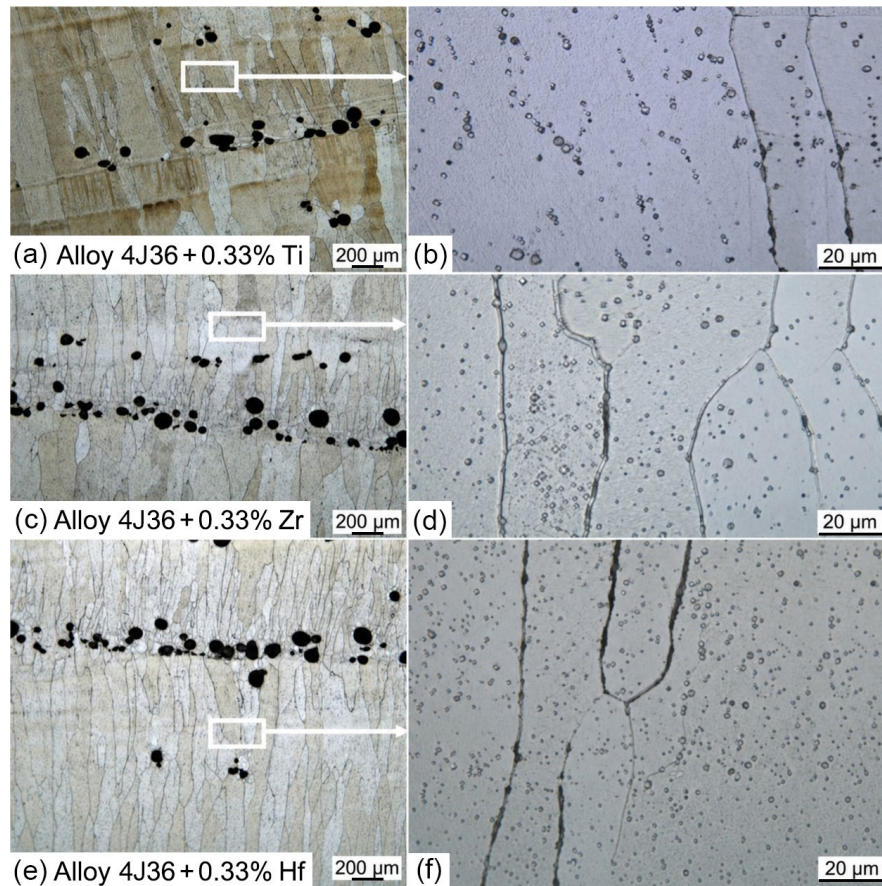


Fig. 13: Microstructure of Invar alloys with different components: (a) 4J36+0.33wt.% Ti; (b) enlarged area of (a); (c) 4J36+0.33wt.% Zr; (d) enlarged area of (c); (e) 4J36+0.33wt.% Hf; (f) enlarged area of (e)^[48]

Table 2: Mechanical properties comparison of different additive manufacturing methods

Process	UTS (MPa)	Elongation (%)	Ref.
L-PBF	345–538	<32	[8]
L-PBF	~480	33	[49]
L-PBF	437–484	34–36.5	[25]
L-PBF	489.3	43.3	[27]
DED	382–592	31–48	[37]
DED	485	36.2	[42]
WAAM	486	29	[47]
Hot-rolled	463	27.1	[50]
ASTM B753-07(2018)	518	34	[51]

Table 3: Thermal expansion properties of 4J36 Invar alloys with different additive manufacturing methods

Process	CTE	Ref.
Cast	2.0 (below 300 °C)	[52]
Hot-rolled	2.14 (room temperature to 200 °C)	[50]
L-PBF	2.0 (room temperature to 200 °C)	[53]
DED	2.88 (100 to 200 °C)	[42]
WAAM	2.0 (room temperature to 200 °C)	[48]
ASTM B753-07(2018)	2.0–2.7 (room temperature to 200 °C)	[51]

3.2 Thermal expansion properties

The thermal expansion properties of 4J36 Invar alloys with different preparation methods are compared in Table 3. The results show that the expansion property of Invar alloy prepared by additive manufacturing is equivalent to that of Invar alloy prepared by traditional method (cast or hot rolled). In particular, the CTE of the sample prepared by L-PBF is lower (even negative expansion), which has been mentioned in the study of Huang et al.^[27], but the correlation between the

thermal expansion properties and the process parameters is not clear. At the same time, at present, most of the alloys reported are 4J36 Invar alloy, and there are few reports on other compositions such as Invar 32 or modified Invar alloy.

3.3 Anisotropy

Some studies have noted that the vertical and horizontal mechanical properties of additive manufacturing Invar alloy show anisotropy. No matter L-PBF, DED, or WAAM, there are certain differences in vertical and horizontal properties. Compared with samples in the vertical (V) direction, samples in the horizontal (H) direction exhibit superior yield

strength (YS) and UTS, as shown in Table 4. At present, the anisotropy of the coefficient of thermal expansion in additive manufactured Invar is disputed by scholars, and most explanations focus on internal defects and residual stresses^[8, 37]. Some studies believe that the method of heat treatment is an effective way to achieve the isotropy. The vertical and horizontal properties of Invar alloy tend to be the same after heat treatment, but the mechanical properties of Invar alloy are reduced^[37, 48].

As shown in Fig. 14, through magnetic properties testing along different deposition directions, it is illustrated from the magnetic point of view that the thermal expansion coefficient of additively manufactured Invar alloy shows little difference and tends to be isotropic, while more research on

Table 4: Comparison of vertical and horizontal mechanical properties of different additive manufacturing methods

Process	YS (MPa)	UTS (MPa)	Elongation (%)	Ref.
L-PBF-H	400	538	25	[8]
L-PBF-V	325	440	29	
DED-V	326	544	39	[37]
DED-H	361	590	31	
WAAM-H	357	539	29	[48]
WAAM-V	321	487	27	

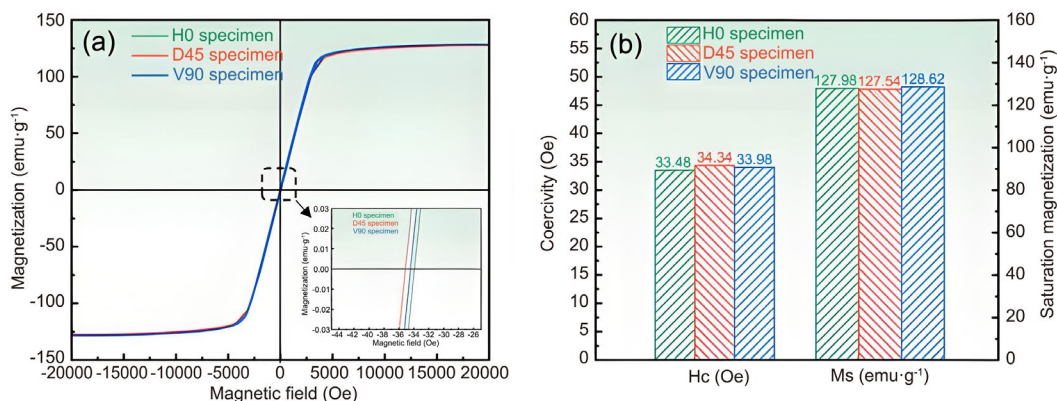


Fig. 14: Effect of anisotropy on magnetic properties (thermal expansion properties): (a) hysteresis loops at room temperature; (b) saturation magnetization and coercivity^[54]

it has not been reported at present. Most studies attribute it to the anisotropy of the microstructure and the distribution of defects^[59]. Through specific processes, this anisotropy can be retained or even harnessed, enabling the design of alloys with better performance for different application scenarios.

4 Applications of additively manufactured Invar alloys

4.1 Precision structural components

As a low-expansion alloy, Invar alloy is characterized by its low thermal expansion and high toughness, making it an excellent candidate for structural and support components. However, its high density and general machinability limit its applications. In traditional manufacturing processes, reducing density without changing materials can only be achieved through structural design, which demands higher machinability. Complex structures involving features such as hollows are particularly challenging to produce using conventional methods. Additive manufacturing offers significant advantages in the production of complex structures^[55]. In particular, many lattice structures have been reported to be effective ways to achieve lightweight. In 2014, the journal “Science” reported on novel materials constructed using artificial cells, highlighting their exceptional performance in high load-bearing and zero

expansion, which promises significant breakthroughs with the advancement of additive manufacturing processes^[56]. Furthermore, research has shown that lattice structures, when used as structural components, exhibit high specific stiffness and strength^[57]. The extraordinary properties of lattice structures are not only related to the composition of the base material but also heavily depend on the spatial topology of the artificial cell units, offering broad application prospects in high load-bearing and zero/low expansion functions^[58].

Ma et al.^[59] utilized L-PBF to fabricate simple lattice structures using 4J36 Invar alloy and conducted both simulations and experimental investigations on the impact of transition radii on the mechanical properties of these structures. The experiments demonstrated that lattice structures can significantly reduce the specific gravity of 4J36 Invar alloy components while maintaining mechanical properties and low thermal expansion property. He et al.^[60] employed L-PBF to fabricate five different triply periodic minimal surface (TPMS) (Fig. 15) structures using 4J36 Invar alloy and confirmed that these topological structures produced through additive manufacturing not only possess low CTE and high toughness but also exhibit excellent energy absorption and mechanical properties. These highlight the tremendous advantages of additive manufacturing Invar alloy in the field of high-precision structure fabrication. However, there is limited development of mechanically reinforced lattice structures for Invar alloys, and

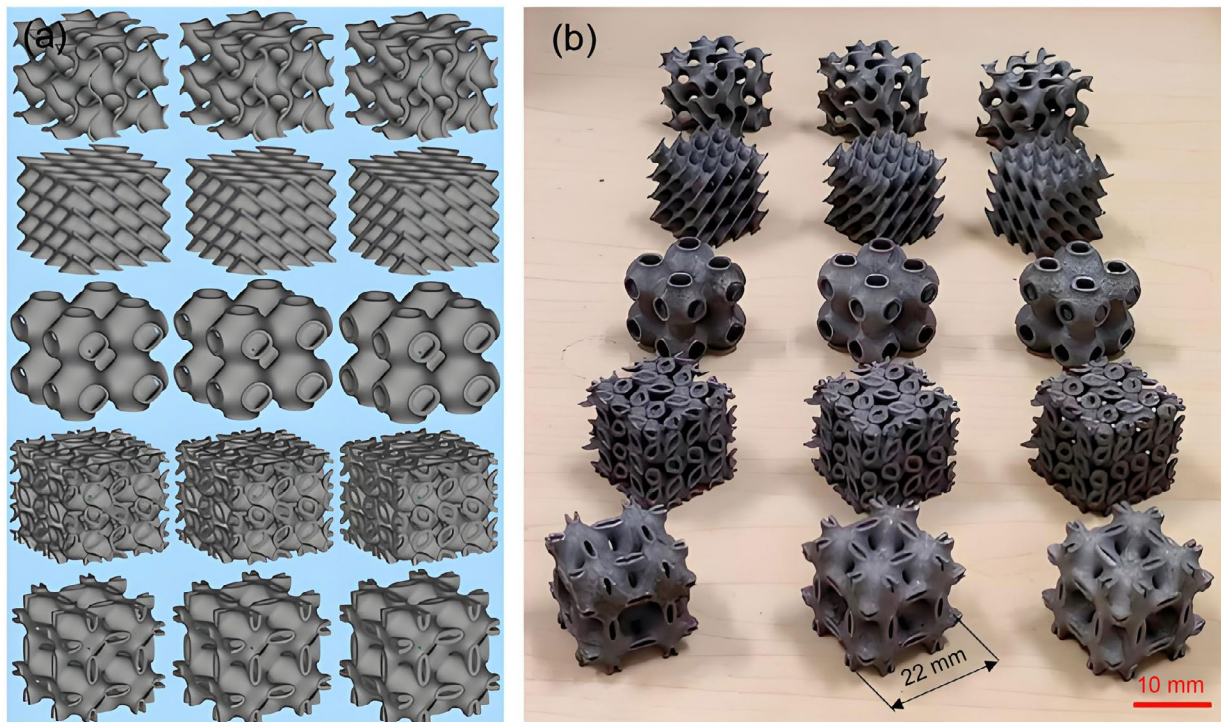


Fig. 15: Five types of TPMS with varying wall thicknesses: (a) CAD models; (b) actual samples^[58]

manufacturing techniques in this field generally lag behind structural development. Extensive experimental research is still needed to support and accelerate their engineering applications.

4.2 Mold material coatings

For large-scale precision molds, it is essential to control the thermal deformation of their contact surfaces to ensure

accuracy. Invar alloy, with its low CTE, excellent plasticity and toughness, and corrosion resistance, is an ideal material for coating the surfaces of molds used in manufacturing large precision components. Figure 16 illustrates a steel mold coated with 4J36 Invar alloy^[61]. Using an Invar alloy coating on the mold surface not only maintains thermal expansion within a high precision range but also significantly reduces material costs^[61].

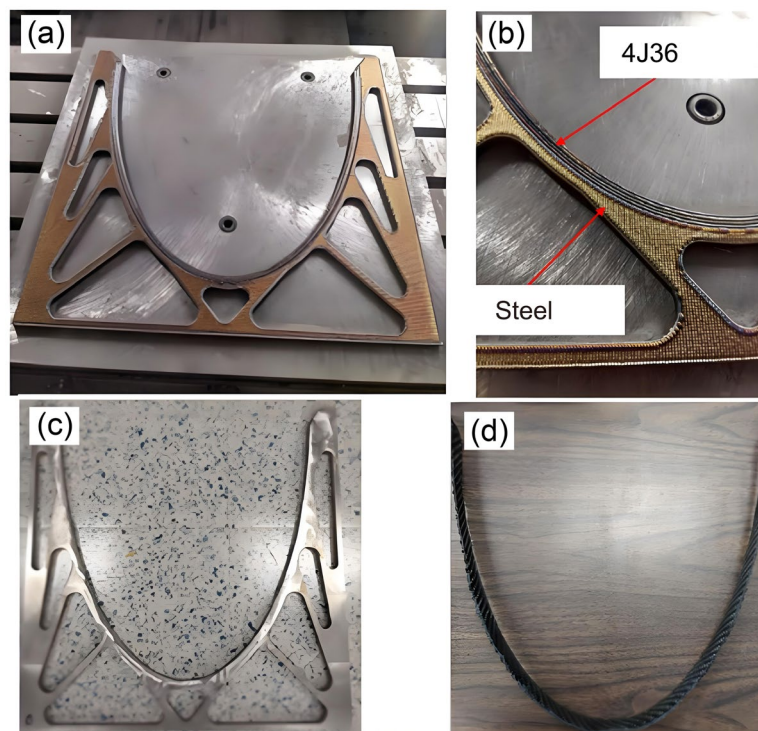


Fig. 16: Steel molds coated with 4J36 Invar alloy using DED technology (a)–(c), and material manufactured by Invar alloy mold (d)^[61]

Coating manufacturing methods include chemical vapor deposition, electroplating, and laser cladding, among others. For most metal coatings, laser cladding offers significant advantages due to its low cost, high efficiency, and high precision^[62]. This technique provides a modified or repair layer with the desired properties for the workpiece and is essentially an application of DED^[63, 64]. Zhang et al.^[65] compared the microstructure and mechanical properties of single-pass and multi-pass cladding of 4J36 Invar alloy on steel surfaces. They found that, under the same parameters, single-pass cladding of Invar alloy resulted in coatings with more uniform and regular grains, as well as superior mechanical properties and wear resistance. This phenomenon is likely due to the remelting and recrystallization processes that occur during multi-pass cladding. Similarly, Wang et al.^[66] conducted an in-depth study on the effects of printing parameters and the addition of Al/Ti elements on the single-layer 4J36 Invar alloy coating on mold surfaces. The results indicated that an Invar alloy coating with 6% Ti addition exhibited excellent mechanical properties under appropriate process parameters.

Surface coating with Invar alloy has long been an effective method for significantly reducing the manufacturing costs of large molds. Among various surface coating techniques, laser surface cladding stands out for its advantages and has garnered attention from some researchers. However, current research on laser surface cladding of Invar alloys typically focuses on specific production contexts, with 4J36 Invar alloy being the commonly used material. There remains a need for extensive, systematic simulation studies and experimental validation in the field of laser surface cladding for high-precision molds and other compositions of Invar alloys.

4.3 Functionally graded materials

Functionally graded material (FGM) is an innovative type of composite material composed of two or more materials with continuously varying composition and structure. These materials are designed to meet the demands of extreme environments in industries such as aerospace, automotive, biomedical, and defense. Invar alloys are known for their unique and adjustable thermal expansion properties, but they typically have low strength. Therefore, they are often combined with high-strength materials such as Ti-6Al-4V to achieve a balance of low thermal expansion and high strength in extreme environments like space. Additive manufacturing technology, with its capability to produce complex structures, also allows for the convenient and rapid alteration of local material composition, making it the optimal choice for fabricating FGM components.

Bobbio et al.^[67] explored the experimental feasibility of creating a linear gradient material of Ti-6Al-4V and 4J36 Invar alloy using DED. By printing transitional materials with a 3% gradient rate layer by layer and conducting related tests, they found that when the Invar alloy content exceeded 18%, the precipitation of various intermetallic phases (FeTi, Fe₂Ti, Ni₃Ti, and NiTi₂) significantly reduced the ductility and toughness of the structure, leading to cracking (Fig. 17)^[67]. In addition, Bobbio et al.^[68] further investigated the cracking behavior, and suggested that eliminating the FeV phase is crucial for successfully manufacturing FGMs with Invar. Fan et al.^[69], aiming to meet the stability requirements of precision instruments in high-vibration environments, developed linear gradient materials of Invar alloy and the

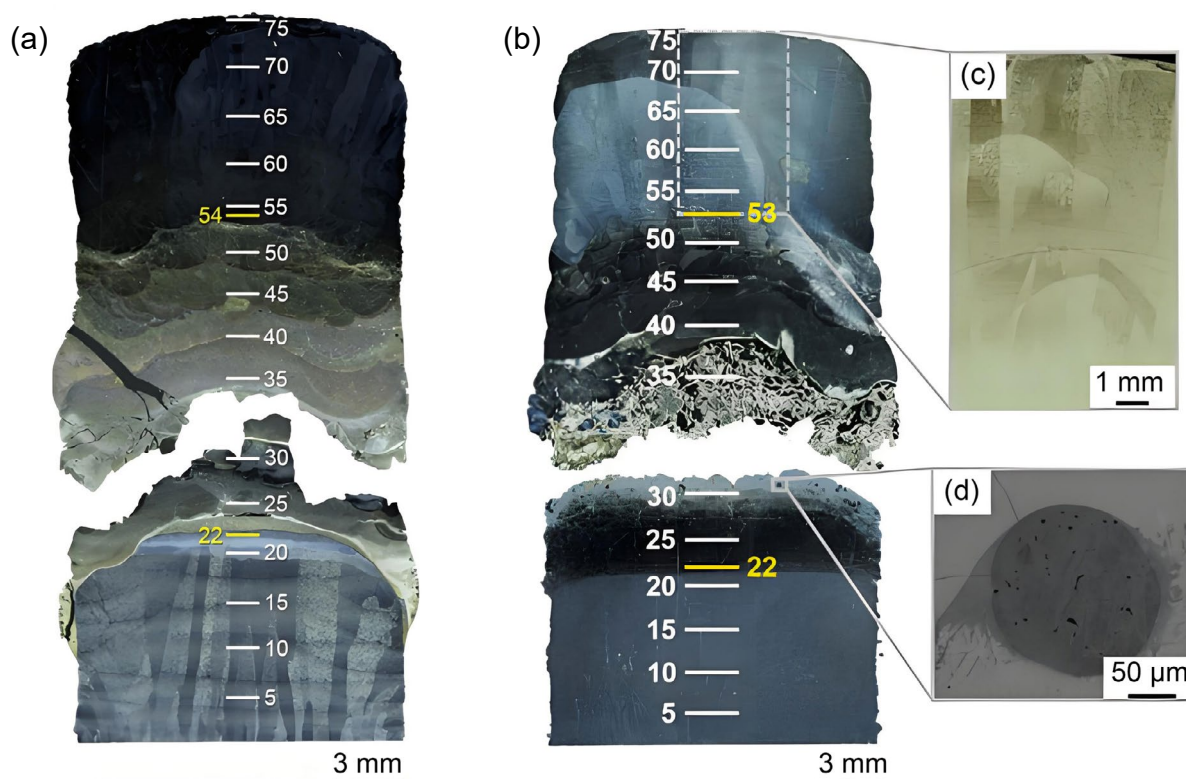


Fig. 17: Schematic of cracking in FGMs of Invar alloy and Ti-6Al-4V or V: (a) Invar/Ti-6Al-4V; (b)-(d) Invar/V^[67, 68]

damping material MnCu alloy using DED. Tensile tests confirmed the presence of the “weakest link effect” in the material, with stress and plastic deformation during fracture concentrated in areas with a higher proportion of Invar alloy, which had poorer mechanical properties.

Currently, there is limited integration of experimental and simulation studies on gradient materials of Invar alloy, with few successful cases. There remains significant potential for exploration in areas such as multi-material systems, high-performance applications, diverse fields, and intelligent technologies.

5 Conclusions and perspectives

As a low thermal expansion material, Invar alloy exhibits significant application potential in various fields, particularly in precision instruments and aerospace. However, its engineering applications are limited by poor machinability and relatively low strength. Traditional methods for manufacturing Invar alloy suffer from difficulty in forming complex components and imprecise composition control. With the continuous advancement of emerging material manufacturing technologies, additive manufacturing has become a powerful tool for developing next-generation high-performance Invar alloys, offering new pathways to discover alloys with superior properties. As technology progresses and materials research deepens, additive manufacturing of Invar alloys will enable precise compositional control, targeted performance enhancements, efficient manufacturing of complex structures, and rapid development of new materials. This will drive new applications and market demand, opening new possibilities for the engineering applications of Invar alloys.

The performance of additively manufactured Invar alloy varies significantly depending on the specific manufacturing process. This imposes higher limitations on the formulation of relevant industry standards. Currently, the existing standards mainly focus on casting and forging Invar alloys, and set relatively fewer requirements for the performance and processing of additively manufactured Invar alloys^[56].

Considering current domestic and international development trends, breakthroughs in additive manufacturing of Invar alloys are still needed from the following perspectives:

(1) Development and simulation of Invar alloy system for additive manufacturing

More Invar alloy compositions should be developed. At present, most of them focus on additive manufacturing of 4J36 Invar alloy system. Expanding Invar alloys with different compositions is a work that should be continued. Current, research on the performance and process parameters of additive manufacturing Invar alloys is generally based on experiments, which limits its ability to guide future studies. There is a lack of systematic simulation research. Reasonable simulation data can not only correctly regulate performance to meet different needs but also further save costs and improve production efficiency. Future additive manufacturing of Invar

alloys should commence with simulation and modeling. Based on an integrated model and specific property requirements, numerical computation and simulation should be performed. Subsequently, process parameters should be adjusted according to the simulation data to produce high-performance Invar alloys. Performance characterization of the alloys should then be conducted, with the experimental data fed back into the simulation step for dynamic optimization. This iterative process ultimately enables simulation-guided production, reducing experimental costs.

(2) Design of Invar alloy compositions

The microstructure and properties of additively manufactured Invar alloys should be further studied, especially on α -Fe phase. Meanwhile, the current development of Invar alloys is mainly constrained by the inefficient research for effective compositions in an almost infinite compositional space. Combining computer-aided material development with additive manufacturing can efficiently develop Invar alloys with specific microstructures and properties. The process should initiate with computer-aided range prediction utilizing integrated simulation and experimental data. Furthermore, high-throughput experiments should be used to optimize the selected components. This integrated approach ultimately yields optimized alloys while refining the predictive model for more precise development of novel alloys.

(3) Development of multi-performance Invar alloys

Although the mechanical properties of additively manufactured Invar alloys have improved compared to that of prepared by traditional processes, they still fall short in some aspects due to the inherent nature of the material, making it difficult to meet certain specialized requirements. Instead of solely developing new compositions, combining Invar with materials that can compensate for its shortcomings offers a wider range of material choices. The high degree of freedom in additive manufacturing processes gives it significant potential in the field of material transition and bonding. Future development of Invar alloys should not be confined solely to their inherent low thermal expansion properties. Instead, it should integrate high-strength materials and other functional materials to ultimately yield multifunctional composites. For instance, in the application of aerospace telescope supports, combining the low expansion of Invar alloys with the damping properties of vibration-resistant alloys enables the additive manufacturing of composite materials. This approach can effectively address requirements for lightweighting and multifaceted performance, offering significant advantages in cost reduction and development cycles shortening.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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