

A novel Ti/Al interpenetrating phase composites with enhanced mechanical properties

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Abstract

Lightweight, energy-absorbing materials with excellent mechanical properties are highly desired in practical engineering applications. A novel Ti-Al interpenetrating phase composite (Ti/Al IPC) was successfully fabricated by filling an Al alloy (ZL102) in the pores of an additively manufactured triply periodic minimal surface (TPMS) structure composed of Ti alloy (TC4). This IPC demonstrates a remarkable combination of attributes, including a high yield stress of 305 MPa, a Young's modulus of 64 GPa, and an ultimate tensile strength of 420 MPa. These mechanical properties are 1.5 to 2.9 times stronger than those of a single TC4 TPMS structure of the same size. The enhanced performance can be attributed to the synergistic strengthening and toughening effect resulting from the internal interpenetration of the ZL102 phase within the structure.

Keywords: Additive manufacturing; Triply periodic minimal surface; Interpenetrating phase composites; Porous structure; Fracture behaviour

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1 Introduction

In industrial applications such as aerospace and automobile, there exists an increasing demand for lightweight and energy-absorbing materials [1, 2]. This demand has encouraged research into advanced composites for better mechanical and functional properties. Metal composite materials obtain superior properties through the mutual cooperation of the constituent materials [3]. Traditional metal composites typically rely on a single metal to serve as the primary load-bearing component, offering rigidity and strength, and other metals or materials within these composites are primarily responsible for facilitating load transmission. The matrix material can maintain a continuous state, while other metals or materials struggle to establish a topological interconnected configuration, potentially restricting the overall performance and capabilities of composite.

Interpenetrating phase composites (IPCs) with two distinct phases interconnected in a topological manner have garnered significant attention from researchers in recent years [4-8]. This unique property plays an important role in preserving the excellent characteristics of a single material while simultaneously mitigating one or more performance defects of the conventional metal composite materials. The collaboration between these two phases can yield outstanding mechanical properties, enhancing the overall performance of the material [9-13]. For instance, the structure of Mg/Ti IPCs imparts the composites with an exceptional combination of mechanical properties, encompassing strength, elongation to fracture, work of fracture, and fracture and impact toughness [14]. The TiC-Fe IPCs exhibit superior attributes surpassing the individual constituent metals in terms of hardness, toughness and structural integrity [15]. In addition, some research experiences have validated that IPCs based on a triply periodic minimal surfaces (TPMS) structure exhibit superior mechanical properties, including extreme performance characteristics [16]. The TPMS structures are characterised by their continuous and smooth infinite periodic surfaces in three independent directions. The surface has a special spatial structure of two disjoint regions in space. The TPMS structure has a multitude of outstanding characteristics [17], including lightweight properties, remarkable energy absorption effect, mechanical property [18], self-supporting attributes, design flexibility and elimination of stress concentration effects [19].

Despite the considerable research efforts focused on exploring the mechanical properties of

TPMS structures, there remains a need to develop a novel composite structure that genuinely combines high performance with low weight. To achieve exceptional mechanical properties in metal composite while adhering to the goal of lightweight design, this study selected Al alloy and Ti alloy as the constituent metal alloys for IPCs. A new Ti/Al IPC metal material featuring a TPMS structure was prepared in this work. The research included an examination and analysis of the morphology and microstructure of the Ti/Al IPC material, and an investigation into its mechanical properties.

2 Material and methods

2.1 Sample preparation

The precise procedure for creating the mathematically designed TPMS structure consists of three main stages: plotting of the implicit equation, ensuring accurate description of structure surfaces, and generating the output of a stereolithographic (STL) 3D model. The designed structural unit is a 10 mm × 10 mm × 10 mm cube. The TPMS structure was prepared by selective laser melting (SLM) method after multilayer stacking, and its sintered powder material is TC4, a high-strength α - β type two-phase titanium alloy. The Ti/Al IPCs were prepared by gravity casting method, and the preparation process is shown in Fig. 1a. The additively manufactured TPMS structure specimen was heat treated at the temperature of 800 °C under the protection of argon for 2 hours, and cooled in the heating furnace. The prepared ZL102 was melted at 720 °C in an argon-protected environment. The molten ZL102 was then poured into a graphite cuvette, gradually filling in the pores of TPMS structure of TC4. In order to ensure the fine grain of Ti/Al IPC and better mechanical properties, the pouring process was conducted in the ultrasonic field. The ultrasonic vibration frequency is 40 kHz, and the ultrasonic cleaning time is 120 s.

2.2 Characterisation

Compression tests were performed with rectangular IPC samples measuring 10 mm × 10 mm × 25 mm at a uniform speed of 2 mm/min. Three repetitive compression tests were conducted on both TPMS structure and Ti/Al IPC specimens, respectively. After the compression testing, experimental specimens were cut from the IPCs. The optical microstructure of composite was investigated by the Nikon Eclipse LV100NDA optical microscope. A JSM-6490F scanning

electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS) capability was utilised to scrutinize the morphology of the interfacial zone and investigate the diffusion of elements.

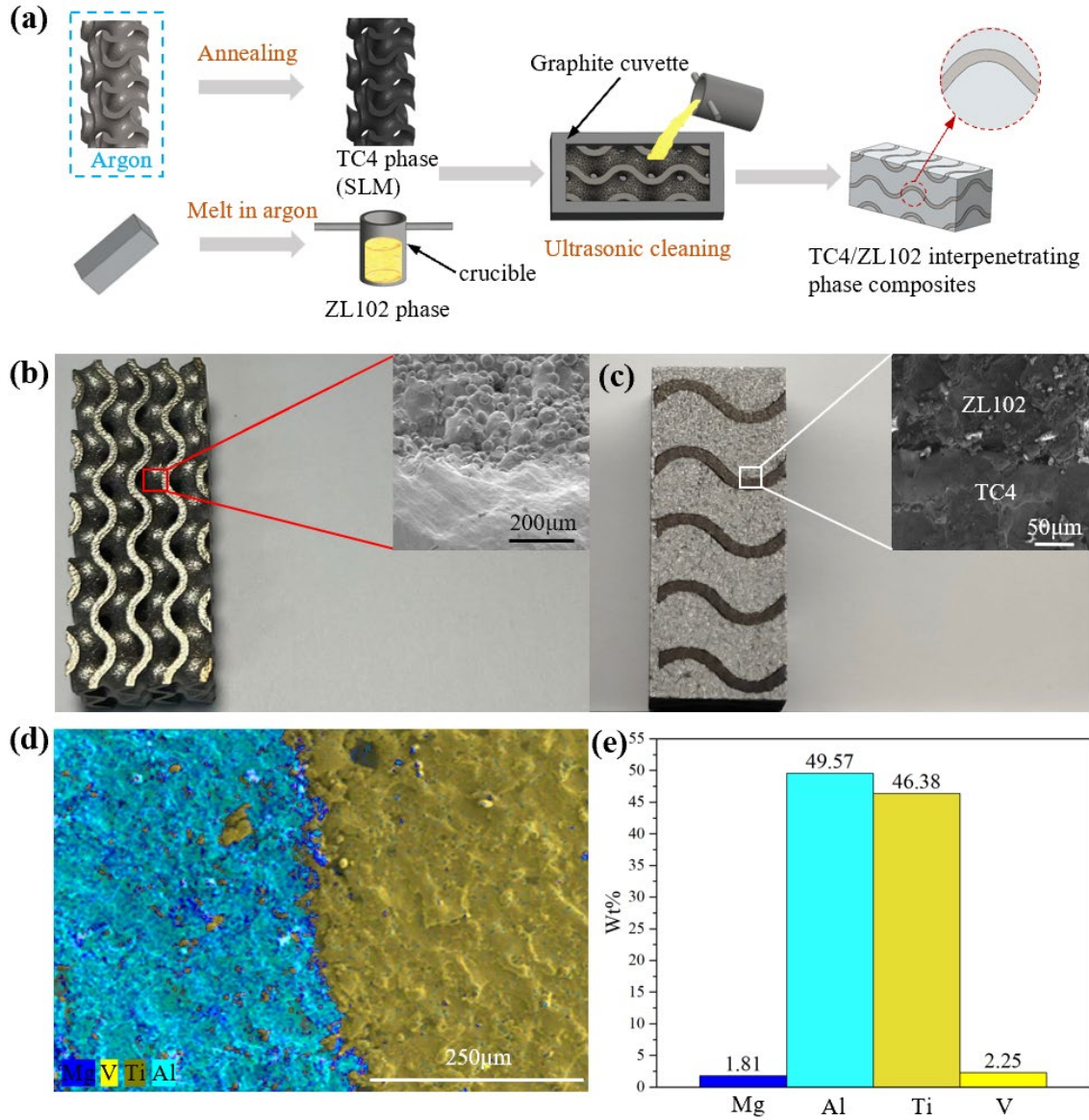


Fig. 1 (a) The preparation process of Ti/Al IPCs, (b) macro morphology of typical TPMS structure, (c) a fabricated Ti/Al IPC specimen, (d) EDS mapping of Ti/Al IPC, and (e) the proportion of each element in Ti/Al IPC.

3 Results and discussion

Fig. 1b shows that the TPMS structure exhibits a porous structure with continuous channel pores, and adjacent pores are connected through channels of rotating surfaces. The porosity of TPMS structure is 67.19 %. In Fig. 1c, it is evident that the Ti/Al IPC material is successfully fabricated, with the ZL102 phase effectively filling the pores of TC4 phase, and there are no

obvious defects at the interface between these two phases. The EDS analysis results, as shown in Fig. 1d, illustrate that due to the influence of gravity casting, there is an interpenetration of elements between the ZL102 and TC4 phases. The primary elements in the IPC comprised 1.81 % of Mg element, 2.25 % of V element, 46.38 % of Ti element and 49.57 % of Al element with the largest content (Fig. 1e). However, the distinct new intermetallic compounds at the interfaces of the two phases in the IPC are not observed. Furthermore, the additively manufactured TC4 scaffolds exhibit a particular surface roughness that facilitates the bonding of liquid ZL102 to the scaffold surface, resulting in the formation of interfacial bonding between the two phases and creating mechanical interlocking [20].

Figs.2a and 2b shows the macroscopic compressive behaviours of TPMS and IPC specimens, respectively, at different strains. The pores within the TPMS structure undergo compression, leading to a reduction in their size, and the structural deformation is significant. When the strain of IPC specimen reached 12 %, the initial crack occurred in ZL102 phase and the initial crack was formed (Fig. 2b). As the strain increases, the ZL102 phase within the pores is pushed out and slides down. Finally, the internal TPMS structure in the damaged area of ZL102 damage, an inclined slip is formed (Fig. 2b), resulting in the failure of the composite. In addition, according to the numerical values of mechanical properties obtained from compression experiments in Fig. 2c, IPCs exhibit substantial enhancements in the yield stress, Young's modulus, ultimate tensile strength, reduction and work hardening coefficient compared to the TPMS specimen. This phenomenon corresponds to the stress-strain curve measured by experiment in Fig.2d. During the compression process, the behaviour of the TPMS structure shows a plateau platform area on the stress-strain curve, due to that the compression of the pores within the TPMS does not significantly increase the stress in the material. In contrast, as the strain increases, the ductile compression of ZL102 causes the stress in the composite to continue increasing. It is worth noting that cracks in the IPC are primarily observed in the ZL102 phase, and these cracks have a tendency to expand outward, causing the ZL102 phase to crack and slide towards both sides. The ZL102 phase plays a supporting role for TC4 phase within the interpenetrating structure, and it possesses the capability to divert and redirect cracks outward at a rapid rate [21]. This process can be more intuitively demonstrated by the force diagram in Fig. 2e. The depiction of the damage process and mechanism of IPC is illustrated

in Fig. 2f. At a strain of 6 %, the structure remains intact, with both phases compressed together. However, upon reaching a strain of 12 %, the initial damage emerges as intergranular cracking within ZL102 phase adjacent to the interface. As the strain reaches 18 % and stress approaches its maximum, the partial separation of TPMS and ZL102 phase becomes evident at the interface, while intergranular cracking near the diffusion zone continues to appear and spread. At this time, the TPMS structure inside the IPC exhibits micro-cracks due to unsintered powder inclusions and pores. This defect appears to be inevitable in metal 3D printing, and the micro-cracks present in TPMS destroy the continuity and integrity of the interpenetrating structure, resulting in a stress drop on the stress-strain curve after this strain [22-24]. Continued compression up to the strain of 24% causes the TPMS structure failing, and all cracks merge, join, and expand, resulting slippage in the IPC and a sharp decline in the stress-strain curve. In general, although the initial cracks appear in the ZL102 phase, it contributes to the IPC by providing ductile compression support and facilitated the outward extension of rapid cracking, thereby improving compression performance. However, the TPMS structure remains the fundamental support for the structural stability of the Ti/Al IPC, and the fracture of its structure ultimately leads to the failure of specimen.

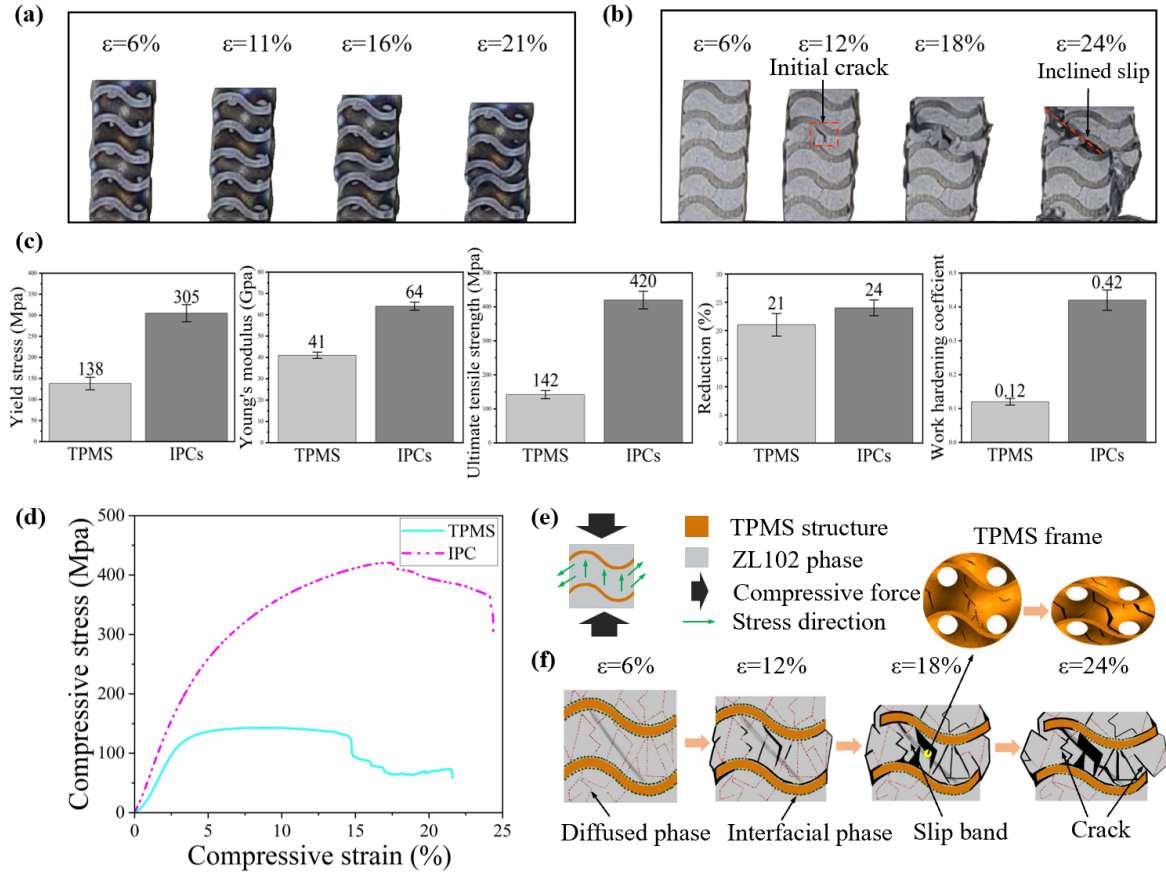


Fig. 2 (a-b) Compressive behaviours of TPMS and IPC specimens, respectively, at different strains, (c) Average compressive properties of specimens after compression test, (d) typical engineering compressive stress-strain curves of TPMS and IPC, (e) the force diagram of structural compression, and (f) the deformation damage mechanism diagram of Ti/Al IPC.

The SEM images of the fracture surface after compression experiment are conducive to the microscopic analysis and further understanding of mechanical properties of IPCs. It is obvious that multiple deboned interfaces are distributed well across the fracture surface (Fig. 3). By observing the fracture surface, small cracks appear at the interface of ZL102 phase and TC4 phase in the pores enclosed by TC4 phase, while fracture and separation occur at the two-phase interface of the outer pores (Fig. 3a). Part of the interface line composed of small cracks is inclined towards ZL102 (Fig. 3b), which implies that ZL102 phase helps TC4 phase strengthen collaboratively during compression, helping to prevent an excessive load on the TC4 phase. Interestingly, TPMS structure is smooth on the outer surface, while there are some rough spherical bumps on the surface of the pores in Fig. 1b, which can be attributed to the challenges in additive manufacturing multi-directional surfaces, but the majority of the gaps between the

spherical protrusions of this IPC are filled shown in Fig. 3c. As for the interfacial debonding of the two phases during the fracture process (circled in Fig. 3c), this external toughening can provide additional energy dissipation and resistance to crack propagation. The remarkable enhancement in mechanical strength and energy absorption properties exhibited by IPCs can be credited to the synergistic effects of strengthening and toughening within this distinctive composite structure.

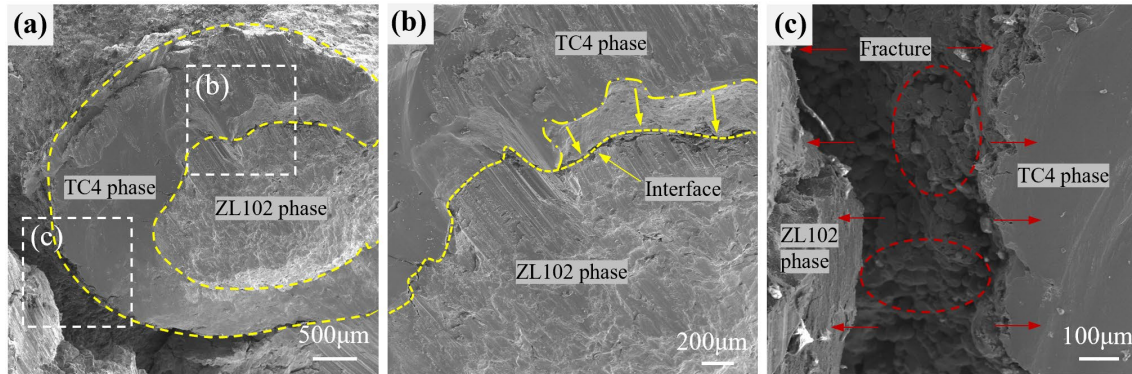


Fig. 3 (a) Fracture surface of the Ti/Al IPC after compression experiment, (b-c) enlarged diagrams between two phases.

4 Conclusion

A novel Ti/Al IPCs material was successfully prepared by gravity pouring ZL102 into the pores of TC4. The prepared Ti/Al IPCs have good mechanical properties on the basis of light weight. The ZL102 phase provides support for IPC in the form of ductile compression, propagating the rapid outward propagation of cracks, and enhancing its compressive properties. This collaboration results in a synergistic strengthening and toughening of the interpenetrating structure. This study provides a new idea for the preparation of IPCs, which could be extended to other high performance structural and functional material combinations.

Declaration of competing interest

There is no conflict of interest.

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