Surface Structuring via Additive Manufacturing to Improve the Performance of Metal and Polymer Joints

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Abstract: In order to enhance the joint performance of Ti6Al4V titanium alloy (TC4) and ultra-high molecular weight polyethylene (UHMWPE) for biomedical applications, different structures were fabricated on TC4 surfaces via electron beam melting (EBM) method in this study. Macromorphologies and microinterfaces of TC4–UHMWPE joints produced via hot pressing technique were carefully characterized and analyzed. The effects of different surface structures on mechanical properties and fractured surfaces were investigated and compared. Strong direct bonding (1751 N) between UHMWPE and TC4 was achieved. The interfacial bonding behavior of TC4–UHMWPE joints was further discussed. This study demonstrates the importance of combining macro- and micromechanical interlocking, which is a promising strategy for improving metal–polymer joint performance. It also provides guidance for metal surface structuring from both theoretical and practical perspectives.

Keywords: metal–polymer joint; surface structuring; mechanical property; interfacial bonding; hot pressing joining

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) exhibits very high wear resistance, impact toughness, chemical resistance, and lubricity due to its extremely long molecular chains (>10⁶ g/mol), and is the most commonly used polymer material in artificial implants [1,2]. Meanwhile, titanium alloy is also widely used in biomedical fields, since it has high strength, good corrosion resistance, and excellent biocompatibility [3]. Combining the advantages of UHMWPE and titanium can improve the biomechanical functions of artificial joints. For example, in artificial temporomandibular joint prostheses, Ti6Al4V titanium alloy (TC4) serves as the main structure to provide strength, while UHMWPE is used as glenoid fossa material to ensure the wear resistance of such joints [4,5]. Therefore, developing effective joining techniques for these two materials is critically important.

The metal–polymer joining techniques mainly include adhesive bonding [6], mechanical fastening [7], and hot-assisted joining or welding [8–11]. However, the potential toxicity of the adhesive or primers used during adhesive bonding mean this method is not suitable for biomedical applications. The usage of screws and bolts in most mechanical fastening processes would cause the concentration of stress, leading to reduction of joint reliability. Heat-assisted joining and welding techniques are promising choices for metal–polymer joining, including injection-molded direct joining, ultrasonic welding, laser welding, friction-based welding, hot pressing joining, and others.
Although these joining techniques have been extensively investigated, it is still hard to form direct bonds between polymers and metals and to obtain joints that achieve excellent performance due to the great differences in physical and chemical features [12]. To enhance the joint strength of non-polar UHMWPE and TC4, mechanical interlocking is a better choice. Thus, complex structures are normally fabricated on the surfaces of metals [8,9,13–18]. For example, inspired by the roots of mangrove trees, Alsheghri et al. [13] introduced a new mechanical interlocking technique to strengthen metal–polymer interfaces by manufacturing Y-shaped features on metallic surfaces using laser sintering. Specifically, the strength of a CoCr–polymethyl methacrylate (PMMA) joint was increased from 2.3 MPa to 34.4 MPa. Additionally, Yeh et al. [16] developed an ultrasonic welding process for acrylonitrile butadiene styrene (ABS) and 5052 aluminum alloy. By structuring grid arrays on the Al plate, they demonstrated that the microscopic structure of the metal plate was a major factor in the joining strength, which promoted the micromechanical interlocking. Until now, there has been little research on the joining of UHMWPE to TC4, except for the work by Chen’s group [9,17,18]. According to Chen et al., UHMWPE and TC4 were successfully joined via friction spot joining (FSpJ), which was achieved by manufacturing a diamond-shaped porous architecture on a TC4 plate via electron beam melting (EBM) technology. Strong lap shear strength (~3000 N) was achieved and fracturing took place in the polymer base material. In that case, the porous architecture played a key role in achieving strong mechanical interlocking.

However, previous studies have indicated that the diamond-shaped architecture might not be satisfactory configurations for complete filling of UHMWPE into TC4 porous layers, leading to macro and microdefects of the joints, although the scaffolds exhibited good structure strength [9,18]. In addition, the pore size, porosity, and strut size would also affect the mechanical strength of the porous architecture, in turn affecting the performance of the joint [19–21]. For instance, the traditional optimum pore size for porous biomaterials used to enhance cell ingrowth efficiency needs to be reconsidered to enhance the joining efficiency of UHMWPE. In principle, improvement of the TC4–UHMWPE joint performance requires an overall inspection of all the above features, indicating that optimization of the surface structure is a key issue. In addition, bioinspired honeycomb architectures with hexagonal cells have also been incorporated in multiscale biomedical applications, with good performance not only in terms of mechanical strength, but also in terms of the heat transfer and high porosity [22]. Nevertheless, the scope of previous research studies was mainly limited to improving the properties of the scaffolds. The effects of the structure design on the interference between metals and polymers during welding or joining have rarely been discussed, especially regarding TC4 and UHMWPE.

In this study, different surface porous architectures were compared to enhance the mechanical interlocking between TC4 and UHMWPE. In this way, we successfully joined UHMWPE plates to 3D-printed TC4 plates via the hot pressing method. Additionally, the effects of the porous surface architecture on the joint performance were investigated. Macromorphologies and microinterfaces were characterized, while fractured surfaces were further analyzed and direct bonding mechanisms were proposed. This study indicates the advantages of combining macro- and micromechanical interlocking and provides guidance for the design of metal surface structures from both theoretical and practical points of view.

2. Experimental

2.1. Base Materials

The UHMWPE (CHIRILEN 1050) used in this work was of high purity and its tensile yield strength was 20 MPa (shown in Table 1). The polymer plate had dimensions of 60 × 20 × 6 mm³. Its melting point was measured to be 137 °C. Owing to the very high molecular weight (>10⁶ g/mol), UHMWPE exhibits extremely high melt viscosity [23,24], with essentially zero melt flow index, which indicates difficulties for joining.
Table 1. Properties of the ultra-high molecular weight polyethylene (UHMWPE) (Chirulen 1050).

| Material | Density  | Melting Point | Yield strength | Elongation |
|----------|----------|---------------|----------------|------------|
| UHMWPE   | 931 kg/m³| 137 °C        | 20 MPa         | 380%       |

The TC4 plate was fabricated with an Arcam A1 EBM® machine using Ti6Al4V powders (Arcam). The chemical composition of Ti6Al4V is presented in Table 2, which was taken from the Arcam specifications. The structure of the metal plate comprised a $60 \times 20 \times 2$ mm³ base bulk part and $20 \times 20 \times 0.5$ mm³ porous layer with different structures. More details will be given later in Section 2.2.

Table 2. Chemical composition of the Ti6Al4V plate (wt%).

| Material | Al | V  | C   | Fe | O  | N  | H   | Ti  |
|----------|----|----|-----|----|----|----|-----|-----|
| Ti6Al4V  | 6  | 4  | 0.03| 0.1| 0.15| 0.01| 0.003| Bal.|

2.2. Surface Structure

Since it is difficult to achieve effective direct bonding between TC4 and non-polar UHMWPE [9,17,18], different surface structures were designed on the metal plates to enhance the macromechanical interlocking. The parameter details of the surface structures are shown in Table 3, while the models and printed plates with different surface structures are presented in Figure 1. In order to study the influence of different surface structures on the interfacial strength, an as-printed, non-structured plate without a porous layer (referred to as “NS”) was fabricated and set as a reference group. In the meantime, a smooth plate (referred to as “SP”) of rolled commercial TC4 was also necessary for comparison with NS for better understanding of the interfacial bonding mechanism between TC4 and UHMWPE and to figure out the effects of EBM method on enhancing the mechanical properties. Therefore, both SP and NS were references for different purposes in this work. It is worth noting that the surface produced via EBM additive manufacturing was rougher than that produced via rolling (as shown in Figure 1a,b). Surface roughness was measured and analyzed using a profilometer (MountainsMap Premium 7.4.8). Additionally, another two types of macroscale structures were constructed and studied. The diamond-shaped architecture (referred to as “DS”) contained a regular tetrahedron as the unit cell, with a strut size of 0.3 mm (diameter). Pore size is generally defined as the distance between two opposite walls of a pore [25]. According to this definition, the pore size of the DS architecture was actually the diameter of the inscribed sphere inside the unit cell, which was 0.9 mm (shown in Figure 1g). Meanwhile, the honeycomb architecture (referred to as “HC”) with a regular hexagon prism as the unit cell was fabricated to reduce the architectural complexity. The strut size and pore size were 0.3 mm and 1.2 mm, respectively (shown in Figure 1h). For all TC4 alloy plates, two $1.1 \times 1.1 \times 10$ mm³ tunnels were designed at the side of the bulk layer to set the K-type thermocouples for temperature measurement at the center and the region located 2 mm from the center (positions A and B, respectively. in Figure 1c).

Table 3. Parameters of different surface structures.

| Group | Strut Size (mm) | Pore Size (mm) | Porosity (%) |
|-------|----------------|---------------|--------------|
| NS    | /              | /             | /            |
| DS    | 0.3            | 0.9           | 71           |
| HC    | 0.3            | 1.2           | 66           |

NS—non-structured; DS—diamond-shaped architecture; HC—honeycomb architecture.
2.3. Joining Technique and Characterization Methods

In this study, joining of TC4 and UHMWPE was performed using a self-designed hot pressing joining system with independent control of the joining force and heat input. A 3D schematic is shown in Figure 2. Before joining, the TC4 plate was fixed using two electrodes, while the UHMWPE plate was placed on a specimen holder. Electrodes were
tightly attached on both sides of the metal plate to conduct the current during joining, leading to a relatively symmetrical temperature distribution.

**Figure 2.** A 3D schematic of the hot pressing joining system.

In order to better control the joining temperature, K-type thermocouples (OMEGA, Norwalk, LA, USA) were inserted into the TC4 tunnels to record the temperature of the lap interface. Figure 3 shows the temperature history during the joining process. Temperatures higher than 250 °C were optimal for joining. Here, although the maximum temperature difference was ~40 °C, the temperature range was still controlled at the appropriate joining temperature (250–300 °C), which was proven by our previous research results [9,18]. Meanwhile, the UHMWPE did not degrade severely until being heated to 400 °C [18]. To enhance the polymer fluidity, a metal plate placed at the bottom was preheated to around 290 °C. Then, the polymer plate was lowered down to contact the metal plate to form a 20 × 20 mm² overlapped joining area. After being pressed and softened, the polymer was filled into the porous layer under a maximum pressure of 5 MPa. The plunge depth was set to 0.5 mm, the same as the thickness of the porous layer. The joint was then cooled down to room temperature while maintaining the pressing head position. It is worth noting that there was a metal baffle between the pressing head and polymer plate, which prevented serious joint deformation during joining.
After hot pressing joining, the joint mechanical performance was mainly characterized by the lap shear testing at room temperature and a stretching rate of 5 mm/min using a Zwick Z020 testing machine (ZwickRoell, Ulm, Germany). As mentioned previously [9,18], a lap joint can resist higher shear force than the tensile yield force of a base UHMWPE plate when the lap joining area is large enough. In order to compare the interfacial strength, the metal part of the joined area was cut through along the central line to halve the shear test area to $20 \times 10 \text{ mm}^2$ (shown in Figure 4). Subsequently, failure was induced at the interface, so as to compare the influence of different structures on the interfacial strength. Furthermore, the remaining unaffected joined part was cross-sectioned later after lap shear testing for microstructural observations. In this way, the microstructural observation and mechanical performance were examined in the same sample. The macroscale morphology of the joints was investigated using a Leica DM 4000 CCD camera (Leica, Wetzlar, Germany) after polishing without metallographic etching. Scanning electron microscopy (SEM, Phenom XL, Phenom-World, Eindhoven, Netherlands) was used for further evaluation of the microscale interface, local elemental composition, and fracture analysis. A thin gold coating was applied to the specimens with a residual polymer to obtain a conductive surface for further SEM investigations. Interfacial bonding was investigated by energy dispersive spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS, Axis Ultra DLD, Kratos, Manchester, UK), and Fourier-transform infrared spectroscopy (FTIR, Nicolet 6700, Thermo Scientific, Waltham, MA, USA).
3. Results

3.1. Macroscale Morphologies of the Joints

Since the non-polar UHMWPE is hard to bond directly to TC4, the joint strength between UHMWPE and the smooth TC4 plate is quite low, which was set as a reference. The SP joints all failed during clamping in the mechanical property tests. Therefore, only macroscale cross-sections of the joints with TC4 produced by EBM additive manufacturing are shown and compared in Figure 5. In the NS group, UHMWPE had intimate contact with the TC4 plate, indicating that UHMWPE easily filled the surface pits formed by the EBM process (shown in Figure 5a). For the DS architecture, many partially fused parts were observed due to the complex cell shape, which reduced the part building accuracy; to be clear, accuracy here refers to how well a finished printed part reproduced the source model. As shown in Figure 5b, non-melted powders still remained inside the porous architecture after joining, while the porous layer and bulk layer were poorly connected. These defects would impede the joining process and reduce the strength of the porous architecture. In addition, the small pore size at the top surface hindered the penetration of the melted UHMWPE. Consequently, the UHMWPE could not completely fill the porous layer, even under high pressure during the welding, due to its high viscosity, leading to many unfilled voids at the interface of the polymer and the bottom of the TC4 bulk layer (shown in Figure 5b). In contrast, the honeycomb architecture with the hexagonal prism cell increased the pore size to enhance the penetration ability of the polymer during joining. The reduced shape complexity resulted in nearly complete filling of the polymer, except for the peripheral area (shown in Figure 5c). It is noted that HC can also form tight bonds between UHMWPE and TC4, without obvious defects.
3.2. Evaluation of Microscale Interfaces

To further evaluate the bonding quality between TC4 and UHMWPE, microscale interfaces of joints were characterized using SEM and are shown in Figure 6. It can be seen that the type of surface structure affected the accuracy of the additive manufacturing. There were large quantities of partially melted metal powder remaining in the pores of the DS group, which were attributed to the complexity of the diamond architecture (shown in Figure 6d). In contrast, NS and HC plates had better forming quality with quite few unmelted powders (shown in Figure 6a,g). Additionally, in the NS group, although UHMWPE easily filled the surface pits, there were still some narrow gaps (5–10 μm) at the interface due to the local stress caused by shrinkage of the polymer during cooling (shown in Figure 6b,c), which was reported and well demonstrated in our previous study [9]. However, the microscale bonding between TC4 and UHMWPE in groups DS and HC was much tighter (shown in Figure 6e,h)—only a few discontinuous gaps with widths of 1–5 μm could be observed in the joints (shown in Figure 6f,i).
Figure 6. Microscale interfaces of TC4–UHMWPE joints with different surface structures: (a–c) non-structured (NS); (d–f) diamond-shaped (DS); (g–i) honeycomb (HC).

Furthermore, the location-dependent interfacial bonding of the joints in the DS group is shown in Figure 7. Similar shrinkage behavior for UHMWPE during cooling was also observed here, leading to microcracks in the UHMWPE at the interface. An EDS mapping approach detected the oxygen-rich element at the interface. The oxygen-rich area only overlapped with the carbon-rich area, which excluded the possibility of titanium oxidation. The oxygen element only came from the UHMWPE itself. Since the UHMWPE itself had no oxygen in its original composition, oxidation of the UHMWPE at the interface was highly possible.
3.3. Mechanical Properties of the Joints

The mechanical properties of the joints of each group were tested and averaged from three samples, and the results are presented in Figure 8 and Table 4. It should be noted that the ultimate force in Figure 8b corresponds to the highest point in the tensile curve shown in Figure 8a. As mentioned previously, since it was hard to form an effective direct bond between the smooth TC4 plate and the UHMWPE, the joint strength (quite low) was set as a comparison, whereby the UHMWPE was barely bonded to TC4. It is worth noting that the joint strength of groups NS, DS, and HC was significantly improved, indicating that modifying the surface via EBM additive manufacturing was an effective strategy to enhance the performance of the metal–polymer joint.

Specifically, the NS group without the porous surface architecture could achieve an ultimate shearing force of 1131 N over 20 × 10 mm². This was mainly due to the high roughness of the as-printed surface, which enhanced the microscale interlocking between TC4 and UHMWPE. However, this did not lead to stable performance, showing a very high standard deviation of 348 N. Compared with NS, the DS architecture increased the ultimate shear force by 45% to 1641 N, however the standard deviation was still high (~280 N). The honeycomb architecture enhanced both the strength and the stability. Correspondingly, the strength of HC was improved by 55% to 1751 N and the standard deviation was significantly reduced to 82 N. Additionally, the ductility of the joints was also influenced by the surface structure. The failure displacement of the NS group was only 0.96 ± 0.53 mm. The HC architecture almost doubled the failure displacement to 1.78 ± 0.44 mm. Meanwhile, the highest result of 2.32 ± 0.44 mm was achieved in the DS architecture, which was 2.4 times that of the NS group.
joints with different surface structures.

Figure 8. (a) Representative force–displacement curves and (b) average ultimate forces and failure displacements for the joints with different surface structures.

Table 4. Mechanical properties of joints with different surface structures.

| Group | Ultimate Force/N | Failure Displacement/mm |
|-------|------------------|-------------------------|
| SP    | /                | /                       |
| NS    | 1131 ± 348       | 0.96 ± 0.53             |
| DS    | 1641 ± 280       | 2.32 ± 0.44             |
| HC    | 1751 ± 82        | 1.78 ± 0.44             |

SP—smooth plate; NS—non-structured; DS—diamond-shaped architecture; HC—honeycomb architecture.

3.4. Analyses of Fracture Surface

To further study the fracture behavior of TC4–UHMWPE joints with different surface structures, the fractured surfaces were analyzed in detail. Figure 9 shows the characterization results. Compared with DS and HC, only a few residues of the UHMWPE polymer remained on the fractured surface (shown in Figure 9a,c). Thus, the joint without the porous surface architecture exhibited weak shear force resistance and low ductility. As we know, the DS architecture provided an interconnecting porous layer. As a result, the polymer matrix provided high resistance against pulling-out effect during the lap shearing test. Large fragments of the teared-out polymer remained after shearing, indicating a locally high joint strength (shown in Figure 9b,d). However, the complexity of the cell architecture impeded the flow of the softened polymer. The insufficient filling of the polymer along with the unfilled voids was the major reason for the instability of the mechanical performance. Additionally, the tilted struts of the DS architecture also increased the difficulty of fabrication using additive manufacturing methods [26]. Large fragments of the TC4 structure were found (shown in Figure 9e) after failure. Although it exhibited the highest failure displacement, its overall strength was relatively low (shown in Figure 8b). However, the HC architecture was somewhat of a trade-off. The simplified hexagonal prism cell design made the filling of the polymer easier during the joining process and full integration of the polymer and metal matrix was achieved. No fracturing of the porous architecture was found after tensile testing (shown in Figure 9f). The relatively decreased porosity enhanced the mechanical strength of the porous architecture [27]. Defects were also diminished due to their reduced complexity [26]. As a result, the HC architecture showed better mechanical strength with less deviation.
Figure 9. Micrographs showing the surfaces after joint failure: (a,c) metal side of the NS sample; (b,d) metal side of the DS architecture; (e) polymer side joined to the DS architecture with large amount of metal residue left; (f) polymer side joined to the HC architecture.

4. Discussions

4.1. Interfacial Bonding Mechanisms

As is known to all, for metal–polymer hybrid joints, on the one hand, the bonding mechanisms directly affect the performance of the joint, while on the other hand, they are the theoretical basis for further optimizing the joint. Therefore, a deep understanding on macroscale and microscale bonding mechanisms is critically important. As mentioned
above, the surface of the metal plate produced via EBM had very high roughness. In order to evaluate the effects of microscale mechanical interlocking, the surface roughness levels and topographies of SP and NS groups were characterized and are shown in Figure 10. It can be seen that the roughness of the NS plate ($S_a = 46.3 \mu m$) was nearly two orders of magnitude higher than that of SP ($S_a = 0.373 \mu m$). Meanwhile, the joint strength of NS was significantly improved from $\sim 0$ N to $1131 \pm 348$ N, which demonstrated that the increased roughness was the main reason for the formation of direct bonding. Obviously, microscale mechanical interlocking plays a leading role in promoting the joint strength of NS. As for the DS and HC, the mechanical properties were further improved, which was mainly due to the contribution of macroscale mechanical interlocking, along with microscale interlocking.

![Image](a) ![Image](b) ![Image](c) ![Image](d)

**Figure 10.** The 3D and 2D morphologies of the surface structures: (a,b) smooth plate (SP); (c,d) non-structured (NS) plate.

In addition, the location-dependent interfacial bonding shown in Figure 7 indicates that the bonding between TC4 and UHMWPE is not only mechanical interlocking, but also effective adhesion. According to the results of Chen et al. [9,18], intermolecular forces such as van der Waals forces and chemical bonding are also important bonding mechanisms in TC4–UHMWPE heterojunctions joined via friction spot joining (FSpJ). In accordance with this, FTIR analysis of the NS sample was performed at the interface after hot pressing, the results of which are shown in Figure 11. A sheared-out polymer plate after lap shear testing was chosen and the top surface was sampled. A referenced UHMWPE was also analyzed. The appearance of an oxidation peak was observed, which corresponded to the carbonyl group spectra ($1710$–$1740$ cm$^{-1}$, shown in Figure 11a) [28]. Combined with the EDS mapping result (Figure 7b), the oxidation phenomenon of the UHMWPE during hot pressing was further verified. Figure 11b shows the XPS analysis on the fractured TC4 side. At the oxygen spectra region, two individual peaks were identified. In addition to the
smaller peak at 529.6 eV indicating TiO₂ [29], the other peak at 532.0 eV demonstrated the existence of organic oxygen peaks attributed to -C=O in UHMWPE [30]. The hot pressing process introduced the carbonyl groups at the UHMWPE surface, which played the role of a bridge, inducing an intermolecular interaction and chemical bonding between these two materials and enhancing the joint strength [9,31–33]. Based on the analysis above, the interfacial bonding mechanisms of the TC4–UHMWPE joint can be mainly attributed to macro- and microscale mechanical interlocking along with van der Waals forces and chemical bonding (through -C=O and Ti), similarly to the results in the FSpJ joint reported by Chen et al. [9].

According to the characterization results and analysis in previous sections, it is worth noting that the effect of the TC4 surface structure design on the joint performance is reflected in many aspects. Firstly, compared with NS, the DS and HC groups improved obviously, both in terms of joint strength and microinterface bonding. It is quite interesting that macroscale mechanical interlocking not only enhanced the strength, but also impeded the shrinkage of the polymer to a certain extent, leading to much tighter interfacial bonding (shown in Figure 6d,f), which demonstrates the importance of combining macro and micromechanical interlocking.

Furthermore, the joint strength, stability, and fracture behavior were also significantly affected by the surface structure. The increased surface roughness produced by the EBM method of course improved the joint performance, however the macroporous architecture can further improve the ultimate shearing force and failure displacement (shown in Figure 8 and Table 4). More importantly, the macroporous architecture can also improve the joint stability, as the joint error bar for the HC group was significantly smaller than that for the NS group (shown in Figure 8 and Table 4). In addition, for the NS group, the failure mode was more similar to a brittle shear fracture. However, the DS and HC architectures showed a tendency toward ductile fracture with much larger displacement.
4.3. Influence of the Complexity of the Porous Architecture

The macro surface structure can strengthen the mechanical interlocking between metals and polymers. Meanwhile, the differences in the macroporous architecture itself can also have an obvious impact. Compared with HC, it was revealed that the failure path of the joints in the DS group was quite complicated, leading to the highest failure displacement due to the failure of the porous architecture. However, it can be seen that the simplification of the architecture of the porous layer (from DS to HC) reduced the difficulty of the manufacturing process. Specifically, based on the metallographic observation of the cross-section (shown in Figures 5 and 6), especially for the HC architecture, it can be seen that the forming accuracy of the structure was improved and the amounts of unmelted powders remaining in the pores were greatly reduced. Meanwhile, no obvious defects were observed in the metal structure of HC itself. Additionally, surface structuring had an obvious effect on the filling behavior of UHMWPE into TC4 porous architecture. For the DS architecture, the polymer did not completely fill into the porous layer. In contrast, the NS plate and the simplified HC architecture (shown in Figure 5a,c) were almost completely filled, with incomplete filling only in the peripheral area. Thus, the simplified structure can allow more effective filling, which is of great significance in guiding the structure design of metal surfaces in order to enhance metal–polymer joints.

In addition, due to the existence of defects (shown in Figure 5), even though the strut size remained the same in DS and HC groups, fracturing of porous layer occurred in the DS architecture, while the fracture of porous layer was less pronounced in the HC architecture (shown in Figure 9e,f), resulting in increased lap shear force. The fracture of the porous architecture also led to the instability of the strength DS group performance, resulting in a larger error bar than that in the HC group. As a whole, although the tearing-out of the polymer in the DS architecture indicated better resistance of the joints against the pulling-out of the polymer, for biomedical applications, especially artificial joint prostheses, TC4–UHMWPE joints would mostly bear shearing and compressing forces rather than out-of-plane forces. From this perspective, resistance to the pulling-out was not the major concern. The better performance in terms of lap shear force and stability suggests that the HC architecture might be a better choice.

5. Conclusions

Metal surface structuring in order to improve the performance of the UHMWPE–TC4 joints produced through hot pressing was investigated in this work. The main conclusions are summarized as follows:

1. The mechanical properties (ultimate force and failure displacement) of the joints were significantly improved through surface structuring via EBM additive manufacturing. Increasing the surface roughness produced via EBM method processing enhanced the microinterlocking between UHMWPE and TC4, while macroscale porous structuring further enhanced the joint performance at both the macro- and microscale;

2. The structure complexity and the defects in additive manufacturing should be considered during the surface structure design. Compared with the diamond-shaped architecture, the simplified honeycomb architecture improved the filling efficiency and the mechanical performance, showing better stability;

3. The interfacial bonding mechanisms of the TC4–UHMWPE joint were mainly attributed to macro- and micromechanical interlocking, along with van der Waals forces and chemical bonding (through -C=O and Ti). Specifically, mechanical interlocking played the dominant role in enhancing the joint strength. Additionally, combining macro- and micromechanical interlocking is a promising strategy to significantly impede the shrinkage of polymer during cooling.
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