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ORIGINAL ARTICLE

Direct joining of 3D-printed thermoplastic parts to SLM-fabricated metal cellular structures by ultrasonic welding

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Abstract
The joining capability of metal cellular structures fabricated using the additive manufacturing (selective laser melting (SLM)) method is investigated herein. The metal cellular structures are composed of sub-millimeter holes and internal pores. The direct joining of 3D-printed ABS-M30i thermoplastic parts to metal cellular structures by ultrasonic welding is demonstrated. The SLM-fabricated structures comprised of partially melted powders provide micro-scale roughness, which enhances the micro-mechanical interlocking between joining parts. A shear strength 17.7 MPa and normal tensile strength of 15.2 MPa were obtained, up to 55 and 48% of ABS-M30i ultimate tensile strength, respectively. Moreover, normal tensile plastic strength up to 86% of the shear strength was obtained.

Keywords Additive manufacturing · Selective laser melting · Ultrasonic welding · Micro-mechanical interlocking

1 Introduction

Plastic metal hybrid parts are gradually being used in engineering applications in the manufacture of items such as automobiles, electronic devices, and in medical application. The use of hybrid structures can not only lead to weight reduction but also increase their functional integration. Nevertheless, current joining methods using adhesive bonding may cause environmental pollution and encounter limitations in medical applications. To solve these problems, the direct joining of plastic and metal materials without the use of additional adhesives has been developed [1]. A common method for doing this involves using an in-mold assembly, i.e., assembling plastic and metal by injection molding [2]. Other methods utilize a thermal joining method, i.e., melting the plastic to produce a plastic metal joint. Methods include friction joining [3–5], direct laser joining [6–9], laser joining with ultrasonic vibration [10], and ultrasonic welding [11, 12]. Recently, a patent issued by Apple Inc. has been presented [13], i.e., ultrasonic bonding of discrete plastic parts to metal. The use of an ultrasonic welding process for the attachment of plastic and metal parts in the manufacture of electronic devices shows much promise.

To enhance joining strength, surface pre-treatments, such as stamping and sand blasting [14], anodizing [15], laser structuring with simple geometry [4, 11], or undercut grooves [8, 16], are used to fabricate different structures on metal surfaces. The plastic-metal bond is obtained when the plastic material solidifies inside these surface structures and mechanically interlocks with the metal part. High joint strength was obtained in structures with a high degree of surface roughness and undercut geometry [6]. However, the structures prepared by the above treatment methods were limited to 2D geometry, with the joint strength of plastic-metal structures limited to a particular direction. For example, the direct joining of injection thermoplastic to laser surface structured metal by ultrasonic welding [12] resulted in normal tensile strength being about two times weaker than the shear strength.

Previous studies on pre-treatment methods employed to fabricate 2D surface structures with enhanced shear strength, and improved normal tensile strength and shear strength have received little attention. Current metal SLM technology provides a unique capability for fabricating complex geometric structures, and is considered a promising technology for advanced manufacturing processes. Recently, SLM-fabricated 2D undercut metal structures joined with plastic structures

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using laser joining was first presented [17]. However, the investigation of metal cellular structures fabricated using the SLM method to enhance joint strengths between dissimilar materials is seldom discussed.

In this study, the direct joining of 3D-printed thermoplastic parts to SLM-fabricated metal cellular structures by ultrasonic welding is presented. Three metallic cellular structures composed of different sub-millimeter circular holes and internal connected channels were fabricated on the metal plate by the SLM process using stainless steel powders. The thermoplastic part, made of ABS-M30i material, was fabricated by the fused deposition modeling (FDM) 3D printing process. The fabricated plastic and metal parts were then directly joined by the ultrasonic plastic welding process. Both the shear strength and normal tensile strength of the joint parts were experimentally studied.

2 Experiment

2.1 SLM-fabricated metal cellular structures

In the studies on joint strength between plastic and metal structures, the proportion of plastic in the joint interface and the internal cellular areas of the metal primarily affected shear strength and tensile strength, respectively. Figure 1 shows the design of the metal cellular structure (size $10 \times 10 \times 1$ mm^3), composed of vertical holes (ΦA) with a depth of 1 mm and varying diameters (0.5, 0.6, and 0.7 mm) for the plastic material to be formed into the metal structures. The distance between adjacent vertical hole edges is 0.2 mm. Each vertical hole has four circular pores (ΦB, diameter 0.4 mm) connected to the other holes. The design specimens with different vertical hole diameters of 0.5, 0.6, and 0.7 mm are designated as D0.5, D0.6, and D0.7. The total vertical holes for the three specimens are 196, 144, and 121, respectively. The surface structure density (the total area of vertical holes compared to the overall surface, i.e., 10×10 mm^2) are calculated to be 0.39, 0.41, and 0.47, respectively.

The metal cellular structures were fabricated on the 304 stainless steel plate (size $48 \times 18 \times 2$ mm^3 using an SLM technique; EOSINT M 280 machine, EOS). During the SLM process, stainless steel powder (EOS PH1) with an average particle diameter of 30 μm was processed with a layer thickness of 30 μm. The parts were fabricated using the processing parameters provided by this machine in order to fabricate SLM parts with full density.

Figure 2 shows photographs of SLM-fabricated structures on steel plate for D0.5, D0.6, and D0.7, respectively. From the magnification images, it was found that some micro-powder particles (indicated by the arrow) adhered to the surroundings of these holes. During the SLM process, the heat-affected zone around the laser-induced molten pool will partially melt the surrounding powder particles and attach them to the sides of the solid part [18]. These micro-scale areas of roughness resulting from partially melted powders around the structure may be helpful in the impregnation of plastic, and provide additional anchor force for the joint parts.

2.2 FDM-fabricated thermoplastic structures

The dimension of the design thermoplastic part is shown in Fig. 3a. It is a kind of "boss structure" for the plastic and metal part connection. The outer diameter is 8 mm and height is 15 mm. The inner hole with a diameter of 4.6 mm and a depth of 12 mm is used to fix the M5 screw for the strength tensile test. In Fig. 3b, the building direction of the FDM process is perpendicular to the direction of ultrasonic vibration. The advantage is that layer gaps along the ultrasonic vibration direction in the 3D-printing process are minimized, and energy transmission loss is reduced. The joining area between the thermoplastic and metal

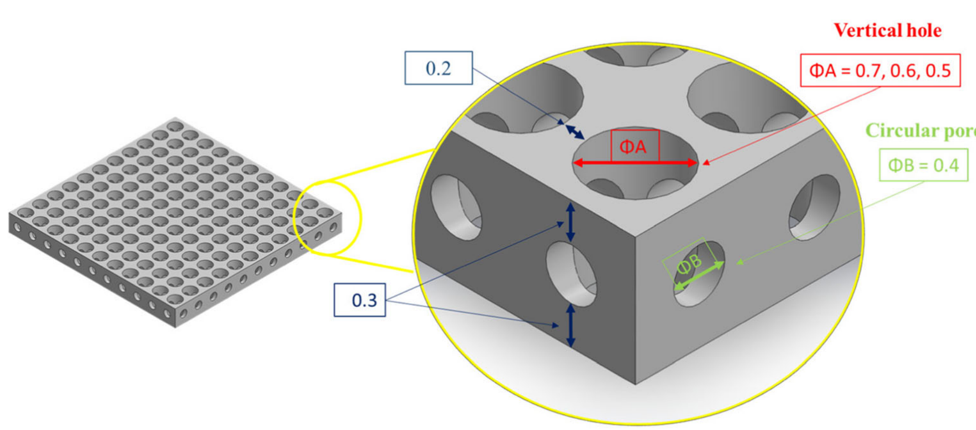


Fig. 1 Schematic of the design metal cellular structure

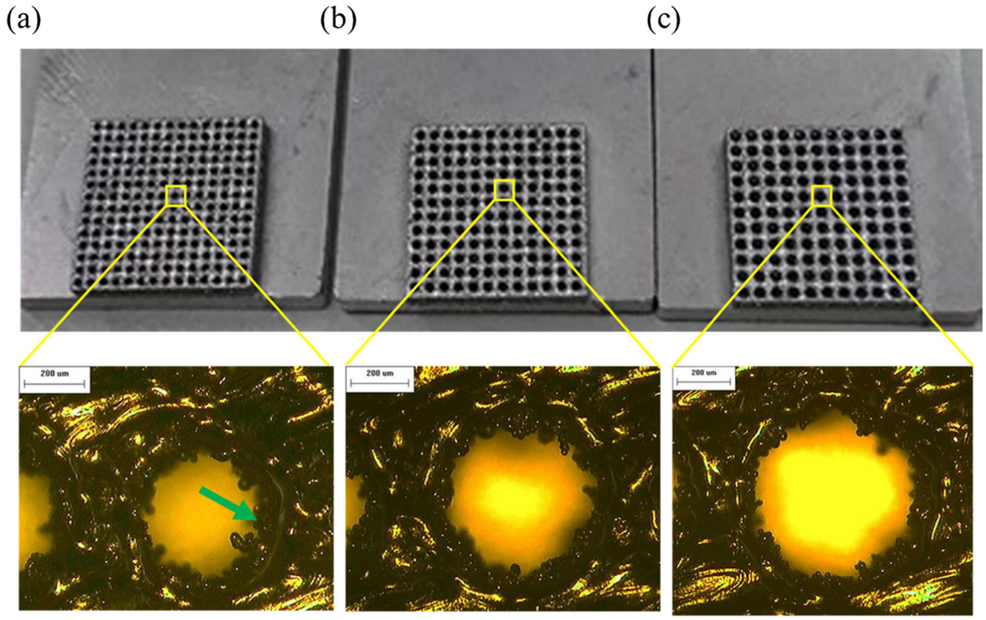


Fig. 2 Photograph of fabricated SLM-fabricated structures for specimen **a** D0.5, **b** D0.6, and **c** D0.7

interface is 50.265 mm^2, which is used for the calculation of tensile strength.

The thermoplastic parts were fabricated using an FDM technique (Fortus 380mc machine, Stratasys) with ABS-M30i filament material. The ultimate tensile strength of this material by XZ printing orientation was 32 MPa [19]. The parts were fabricated using the processing parameters provided by this machine. In order to obtain a flat surface for the joining area and sonotrode contact surface, the printed samples were post-processed by the tuning process. Figure 3c, d are photographs of the top and bottom views of the printed samples after post-processing.

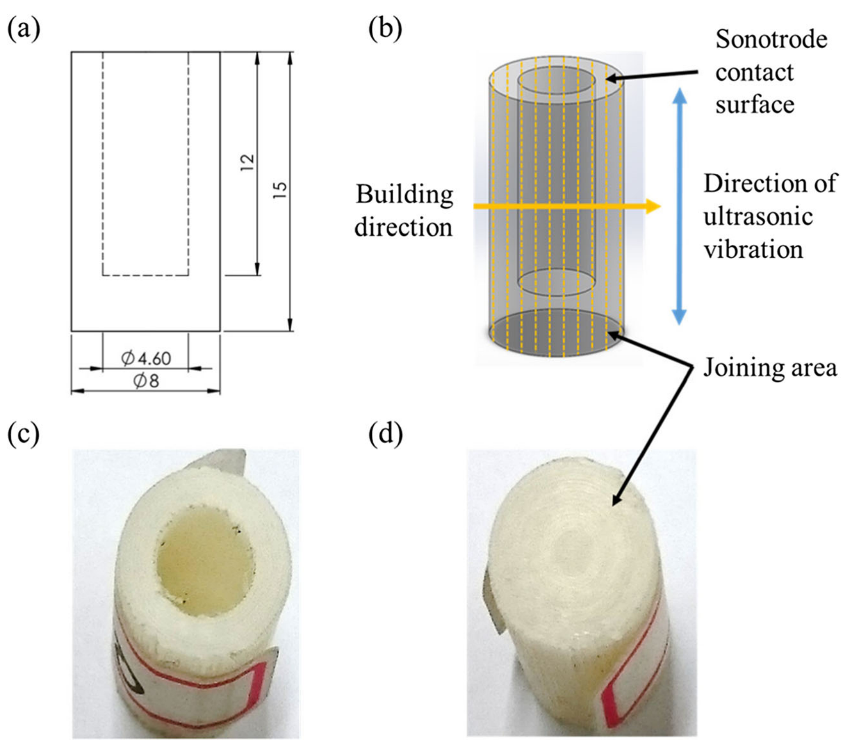


Fig. 3 **a** Schematic of the design thermoplastic part. **b** The building direction for the FDM process. **c**, **d** Photographs of the printed samples for top and bottom views, respectively

2.3 Ultrasonic welding joining process and experimental setup

Figure 4a presents the joining process of ultrasonic welding. Ultrasonic welding requires the sonotrode to contact the thermoplastic and metal under pressure, with ultrasonic vibration applied by the sonotrode on the joining part. Heat is generated at the plastic/metal interface owing to friction or plastic deformation. The direction of the ultrasonic vibration is perpendicular to the joining area. To prevent the SLM structures from being damaged directly by the sonotrode, the plastic part is placed between the sonotrode and the metal surface.

Figure 4b is a photograph of the experimental setup for ultrasonic welding using an ultrasonic plastic welder (KWD2020, k-sonic Inc.). The frequency is 20 kHz and the maximum output power is 2 kW. The steel plate with a SLM-fabricated structure was placed in the fixture, and the FDM-fabricated thermoplastic part was placed on it. In the experiments, the parameters of ultrasonic welding were the vibration amplitude of the sonotrode at 147 μm, pressure at 1.5 kg/cm^2, a delay time of 1.8 s, and a hold time of 1.0 s. The welding time varied from 0.2 to 0.3 s.

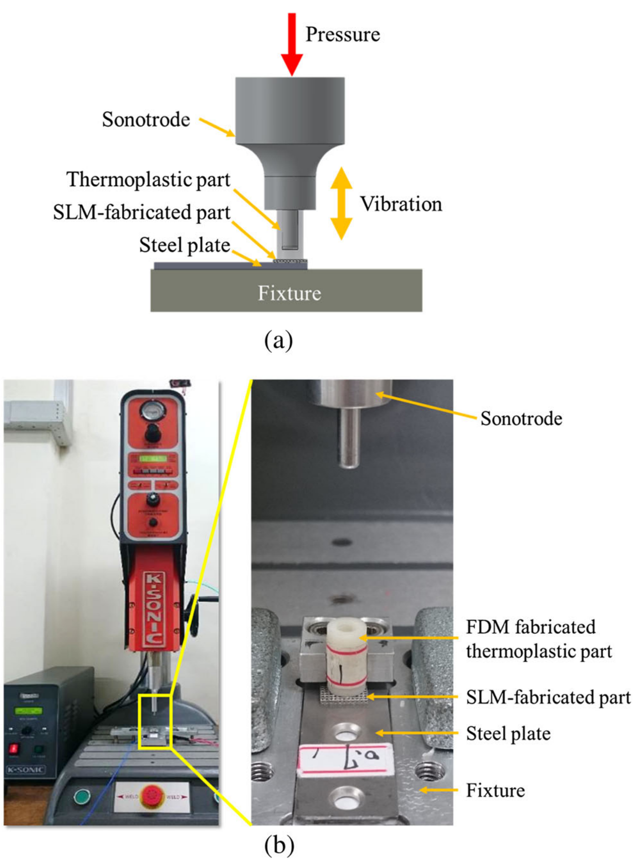


Fig. 4 **a** Ultrasonic welding process and **b** photograph of the ultrasonic welding experimental setup

2.4 Measurement

The joint strength tests were measured by a tensile material testing machine (MTS 810). Figure 5a, b shows the schematic structures for the shear and normal tensile strength testing, and Fig. 5c shows a photograph of the experimental setup for normal tensile strength testing. Both the shear and normal tensile tests were performed at room temperature with a 100-kN load cell and a constant tensile velocity of 1 mm/min. For each of the joining parameters, three specimens were tested to obtain the average tensile strength and standard deviation. Joint strength was calculated based on the maximum load and the joining area of 50.265 mm^2.

The fabricated metal and plastic surface structures, a cross section of the joint structure, and the fracture plane after the strength tests were examined by optical microscope and scanning electron microscope (SEM).

3 Results and discussion

3.1 Ultrasonic welding parameter setting

Figure 6 shows photos of ultrasonic joint specimens D0.7 with welding times of 0.25, 0.3, 0.35, and 0.4 s, respectively. Flash plastic material around the joint area (marked by arrow) was found as the welding time increased.

Table 1 shows the flash conditions and reduction heights resulting from different welding times. The reduction height is defined by the difference between the measured total height of the thermoplastic part and the SLM structure before and after the ultrasonic joining process. The criterion of flash condition was evaluated in the cases where residual plastic material was found around the joint area.

In Table 1, the reduction height was increased with the increased welding time. When the welding time was increased to 0.3 s, the reduction height was not obviously changed, but the degree of flash plastic was more apparent. At a welding time of 0.45 s, the reduction height suddenly increased to 1.2 mm; an obvious flash was found and the plastic part was partially broken. It is presumed that when the welding time is increased above 0.3 s, the molten plastic almost fills and solidifies within the free space volume inside the SLM structure. If the molten plastic cannot flow to the inside of the SLM structure, the residual molten material results in a flash around the surface of the joining area.

Because a lower welding time is better for mass production, the best welding time in the following experiments is chosen as the minimum value of welding time needed to achieve a stable reduction height, e.g., 0.3 s for the specimen D0.7. Table 2 shows the welding time setting for the different specimens. It was found that the welding time and reduction height were increased as the

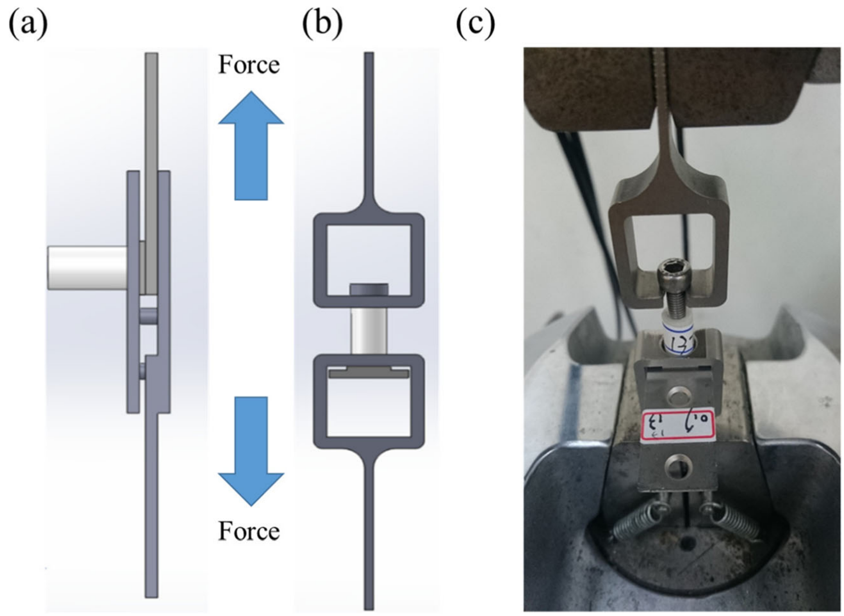


Fig. 5 Schematic structure for the **a** shear and **b** normal tensile strength testing. **c** Photograph of the experimental setup for the normal tensile strength testing

vertical hole diameter increased, since the hollow area of the metal parts was increased as the hole diameter increased.

3.2 Analysis of joint characteristics and fracture plane

To analyze the joint characteristics, the ultrasonic joint specimens were cut perpendicular to the SLM structure joining area, embedded in epoxy resin, and then ground and polished. Figure 7 shows the cross-section SEM images of the joining area for specimens D0.5 and D0.7, respectively. It can be seen that solidified plastic filled the well inside the SLM structures, i.e., the vertical hole and circular pore (see Fig. 1); only a few air pockets were found at the bottom area (near the steel plate). By viewing the magnification images, it was found that the plastic fully contacted the edge of the structure. High-density plastic completely filling the inside of the SLM structures and good adhesion between the plastic and metal structure was obtained. Consequently, the desired three-dimensional micro-interlock between the plastic and metal parts was formed.

When the joint structure was subjected to external forces, the workpiece gradually deformed and broke at the lower strength area, i.e., at the interface between the plastic and metal. Figure 8 shows the fracture planes on the metal surface (specimen D0.5) after shear and tensile testing. In Fig. 8a, it can be found that the deformed plastic material was retained inside the holes. In Fig. 8b, the fracture plane is partially covered with residual ABS materials on the metal surface. These fracture planes for shear and normal tensile testing indicate that the plastic is anchored by the metal cellular structures. From the magnification SEM images, it can be found that the partially melted powders remained in the metal structures after strength testing. This indicates that the SLM-fabricated structures with micro-scale roughness provided by partially melted metal powders around the metal structure attain additional micro-mechanical interlocking force as a result.

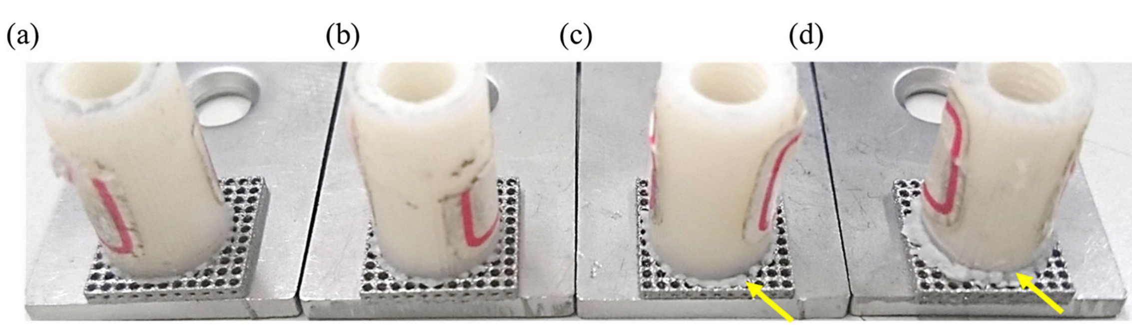


Fig. 6 Photos of joint specimens D0.7 by welding time **a** 0.25, **b** 0.3, **c** 0.35, and **d** 0.4 s. Arrows indicate the presence of flash

Table 1 Flash condition of specimen D0.7

Welding time (s)	Reduction height (mm)	Flash condition
0.25	0.45	No
0.3	0.6	Slightly
0.35	0.6	Yes
0.4	0.6	Yes
0.45	1.2	Obviously

Table 2 Welding time setting for the different specimens

	D0.5	D0.6	D0.7
Welding time (s)	0.20	0.25	0.30
Reduction height (mm)	0.32	0.46	0.60

Figure 9 shows the fracture planes on the plastic surface (specimen D0.5) after shear and tensile testing. In Fig. 9a, it can be found that some deformed plastic material was retained in the location of holes. In Fig. 9b, it can be found that a layer of plastic material removed in the joint interface.

3.3 Strength of ultrasonic welded plastic/metal parts

Figure 10 shows the averaged shear strength and normal tensile strength with standard deviation for the joint specimens D0.5, D0.6, and D0.7. The shear strengths were all higher than the normal tensile strength. In addition, the strengths were all increased as the vertical hole diameter (or structure density) increased. The experimental shear strengths for D0.5, D0.6, and D0.7 were 13.9, 16.4, and 17.7 MPa, respectively. In the same joining area, when the structure density increases, more plastic can be melted into the structure. If the joint sample is subjected to external force in the shear stress direction, more plastic material is required to overcome the deformation and enhance the shear strength. For D0.7 (structure density 0.47), about 55% of the strength of the ABS-M30i material (32 MPa) were obtained. In a previous study, nearly 50% of the material breaking force in the shear strength tests were reached for PC plastic joined with stainless steel with a structure density of 0.55 [20].

The experimental normal tensile strengths for D0.5, D0.6, and D0.7 are 12.6, 13.0, and 15.2 MPa, respectively. For D0.7 (structure density 0.47), about 48% of the strength of the ABS-M30i material (32 MPa) were obtained. It is found that the average normal tensile strength can reach about 86% of the average shear strength, which is much higher than the current research involving surface texturing as a means to improve bonding (about 50%) [12]. When plastic is formed within the internal circular pores and when there is micro-scale roughness around the structures, additional mechanical interlocking force is achieved in these joints. Therefore, such a joint interface is able to bear greater shear loading than joints formed using the conventional surface texturing technique.

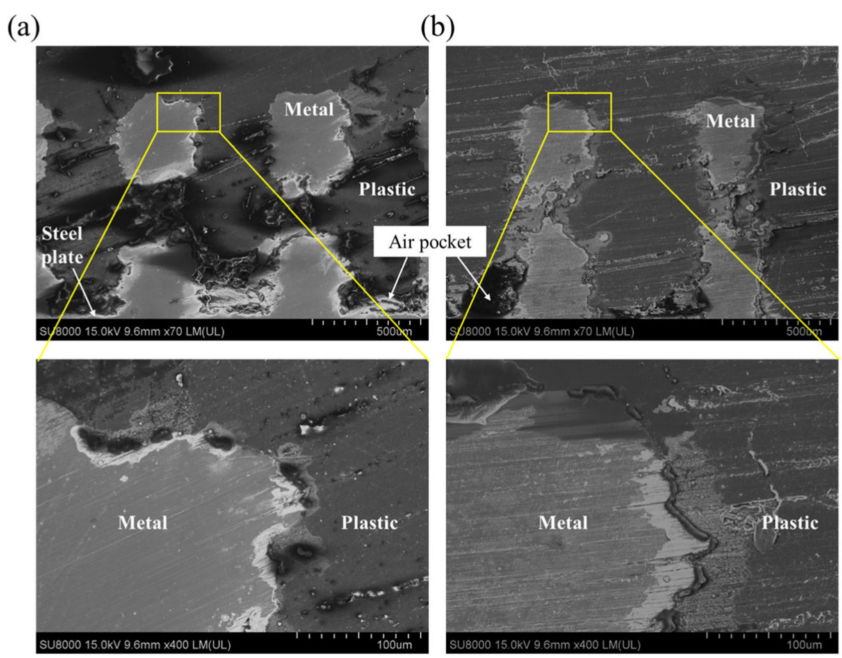


Fig. 7 Cross-section SEM images of the joint structure for specimen **a** D0.5 and **b** D0.7

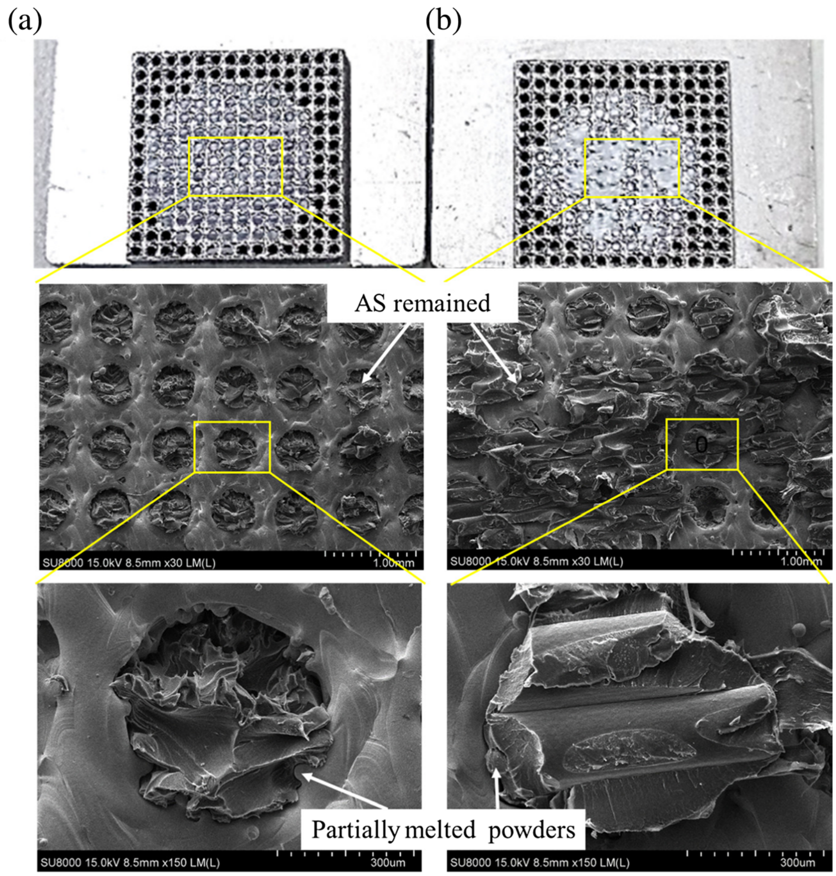
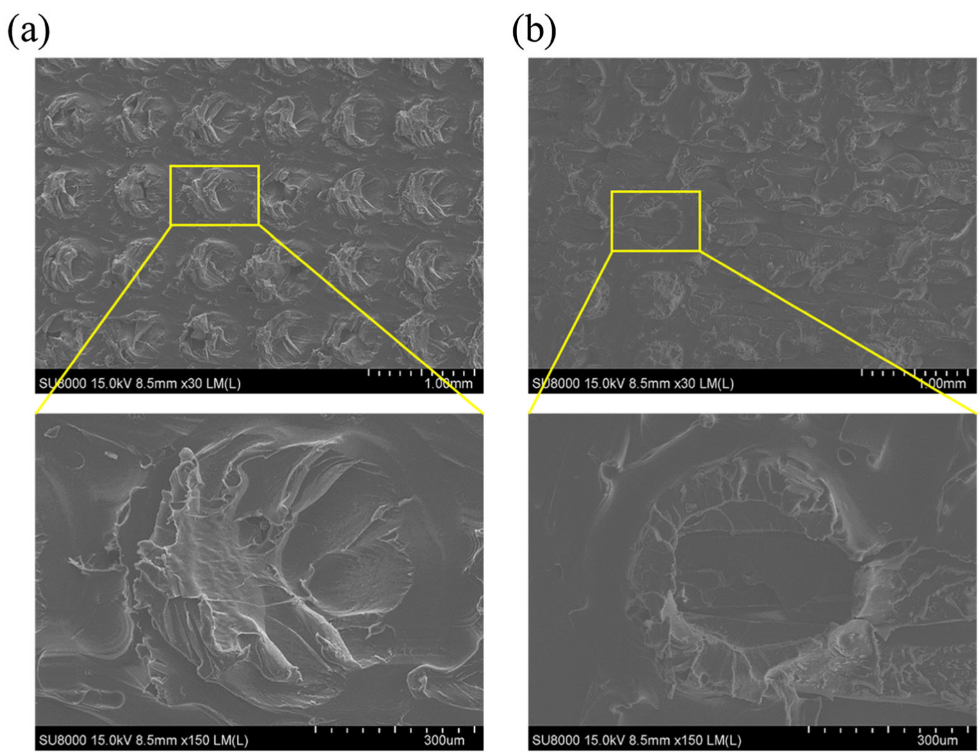


Fig. 8 Fracture plane on the metal surface (specimen D0.5) after **a** shear and **b** normal tensile testing

Fig. 9 Fracture plane on the plastic surface (specimen D0.5) after **a** shear and **b** normal tensile testing



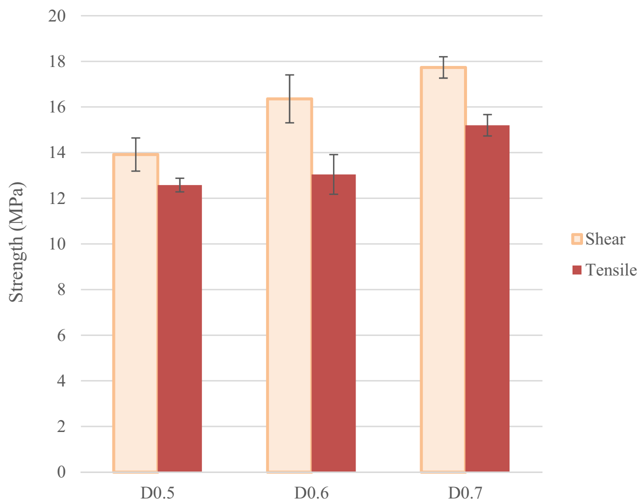


Fig. 10 Joint strengths of ultrasonic welded plastic/metal parts

4 Conclusions

This study demonstrates the use of ultrasonic welding to produce a hybrid structure by the direct joining of thermoplastic ABS-M30i parts to SLM-fabricated stainless steel metal cellular structures. The experimental results and findings can be summarized as follows:

(1) Joint strength is proportional to the structure density of the SLM structure. For specimen D0.7 (structure density 0.47), the maximum shear strength and normal tensile strength are 17.7 and 15.2 MPa, respectively. These are about 55 and 48% of the ABS-M30i ultimate tensile strength, respectively. The normal tensile strength can reach about 86% of the shear strength.

(2) The solidified plastic was almost completely formed into the metal cellular structures to form a large-scale, three-dimensional mechanical interlock. In addition, the plastic can fully contact the partially melted metal powder around the metal structure to form a micro-scale mechanical interlock.

(3) The metal cellular structures can be embedded within metal parts fabricated by the same SLM process, which makes the proposed method ideal for advanced application.

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