Vacuum brazing of binder jetting structures for the assembly of complex internal channels and gyroid lattices

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Binder Jetting (BJ) has emerged as a promising additive manufacturing technology for producing complex metallic components, including lattice structures such as gyroids. Compared to other additive processes, BJ offers advantages in terms of scalability, material versatility, and the ability to fabricate intricate geometries without the need for support structures. However, significant challenges remain in the production of components with closely spaced internal channels and enclosed cavities, particularly due to distortions during sintering and difficulties associated with powder removal.

This work proposes an alternative manufacturing strategy based on the assembly of BJ-fabricated subcomponents through vacuum brazing. The concept involves producing open structures that facilitate depowering and sintering, followed by their subsequent joining to form sealed internal channels. This approach enables the fabrication of geometries that would otherwise be unfeasible as monolithic parts, while minimizing deformation.

Experimental investigations were carried out on representative geometries, including tube-to-tube joints and gyroid lattice cubes joined to plates. Components were fabricated using a metallic BJ process and subsequently brazed in a vacuum furnace. Different filler metals, including Ni-based alloys, active brazing alloys, and pure copper, were evaluated. Brazing parameters were defined, and the resulting joints were characterized by macroscopic analysis.

The results demonstrate that high-quality joints can be achieved using vacuum brazing, with differences observed depending on the filler material. The study highlights key aspects related to joint integrity, defect formation, and filler metal behavior within complex geometries.

Overall, the findings confirm the feasibility of vacuum brazing as a post-processing technique for assembling Binder Jetting components. This approach opens new possibilities for the design and manufacture of advanced structures with complex internal channels and gyroid architectures, particularly in applications where conventional manufacturing routes are limited.

Keywords: Binder Jetting, Vacuum Brazing, AISI 316L Stainless Steel, Triply Periodic Minimal Surface (TPMS), Gyroid Structures, Wetting Behaviour, Capillary Infiltration, Filler Metal Migration, Hybrid Joints, Heat Exchangers

1. Introduction

Binder jetting (BJ) has emerged as one of the most promising metal additive manufacturing technologies owing to its high productivity, scalability, room-temperature printing process, and capability to fabricate geometrically complex components with reduced residual stresses compared with fusion-based additive manufacturing routes. The process consists of the selective deposition of a liquid binder onto a powder bed followed by curing, depowering, debinding, and sintering stages that determine the final dimensional accuracy and microstructural integrity of the component. Despite its industrial potential, challenges associated with densification, shrinkage, defect generation, and dimensional control continue to limit wider adoption of the technology. These aspects have been extensively reviewed in the literature, highlighting the need for an improved understanding of processing-microstructure-property relationships in binder-jetted metallic materials [1,2].

Among the materials processed by BJ, stainless steels are particularly attractive because of their combination of mechanical performance, corrosion resistance, and economic viability. Recent studies have investigated the influence of process variables on densification, microstructural evolution, and geometric accuracy in binder-jetted stainless steels. In particular, dimensional deviations and anisotropic shrinkage have been identified as critical challenges affecting the manufacture of precise components, especially for complex geometries and porous architectures [3,13]. Furthermore, defects generated during powder spreading, binder deposition, debinding, and sintering may significantly affect the final quality of manufactured parts [8].

The ability of BJ to manufacture highly complex lattice structures has stimulated growing interest in triply periodic minimal surface (TPMS) architectures. TPMS structures, and especially gyroid geometries, provide an attractive combination of low density, high specific surface area, mechanical efficiency, and fluid transport capability. The mechanical response of gyroid structures fabricated by binder jetting has recently been demonstrated, confirming the capability of the process to produce cellular architectures with controlled relative density and predictable deformation behaviour [4]. Similar advantages have been reported for gyroid structures produced by laser powder bed fusion, where geometry strongly influences stiffness, strength, and energy absorption performance [5]. In addition, porous TPMS structures based on stainless steels have attracted attention for lightweight engineering applications because of their excellent manufacturability and interconnected pore networks [6].

The combination of binder jetting and TPMS geometries opens new opportunities for the development of lightweight thermal-management devices and compact heat exchangers. In particular, gyroid channels offer enhanced heat-transfer performance owing to their large surface area and continuous fluid pathways, making them attractive for advanced energy and cooling systems [14]. However, the fabrication of highly intricate TPMS structures by Binder Jetting presents additional challenges beyond dimensional control. The removal of unbound powder, debinding of enclosed features, and preservation of structural integrity during sintering become increasingly difficult as architectural complexity increases [3,4,13]. These limitations may restrict the production of large or highly interconnected components and can require complementary post-processing routes capable of reinforcing or assembling complex structures.

Among the available post-processing techniques, vacuum brazing is particularly attractive because it allows metallic joining at temperatures below the melting point of the base materials while maintaining good dimensional stability and limited thermal distortion. The process relies on wetting, capillary infiltration, and diffusion phenomena occurring between the filler metal and the substrates [9]. Previous investigations demonstrated successful vacuum brazing of AISI 316L stainless steel and porous stainless-steel components using nickel-based fillers, showing effective capillary penetration and strong metallurgical bonding [10]. Similar studies on stainless-steel joints highlighted the importance of diffusion phenomena in the development of the brazed microstructure and joint integrity [16].

Nickel-based brazing alloys are especially attractive for stainless-steel applications because of their excellent mechanical properties, corrosion resistance, and compatibility with vacuum-furnace processing. The microstructure and mechanical behaviour of dissimilar joints involving AISI 316L stainless steel and

nickel-based filler metals have been shown to be strongly affected by brazing parameters and diffusion-controlled phase formation [11]. Furthermore, vacuum brazing using Ni-P eutectic filler alloys has proven effective for joining stainless steels in demanding applications, including nuclear systems [15].

The effectiveness of vacuum brazing strongly depends on the wetting characteristics of the filler metal on the substrate surface. Recent studies demonstrated that nickel-based brazing alloys exhibit excellent wettability on both conventionally manufactured and additively manufactured AISI 316L stainless steel. In particular, laser-melted AISI 316L showed enhanced wetting behaviour owing to increased surface energy and diffusion phenomena associated with grain-boundary grooving, which promoted capillary flow of the molten filler metal [12]. Similar wetting behaviour has also been reported for nickel-based fillers deposited on additively manufactured Ti-6Al-4V substrates, confirming the importance of interfacial diffusion and spreading kinetics in joining processes involving AM materials [18].

Additional evidence of the interaction between additive manufacturing and brazing technologies has been reported for hybrid joints combining conventionally produced and additively manufactured AISI 316L stainless steel. These investigations demonstrated that the distinct microstructures generated by additive manufacturing influence diffusion, phase formation, and wetting behaviour during brazing, ultimately affecting joint performance [17]. Likewise, studies on additively manufactured copper alloys highlighted the critical role of wettability, capillary transport, and diffusion phenomena in the formation of sound brazed joints, further emphasizing the relevance of interfacial processes in AM-brazing integration [7].

Despite these advances, limited information is currently available regarding the interaction between brazing filler-metal chemistry and complex Binder Jetting TPMS architectures. Existing studies mainly focus on Binder Jetting process optimisation [8,13], TPMS design and mechanical performance [14], or brazing of dense stainless-steel substrates [15–18]. Consequently, there remains a significant knowledge gap concerning how different brazing mechanisms influence wetting behaviour, capillary infiltration, metallurgical bonding, and filler-metal transport within highly interconnected porous networks produced by Binder Jetting.

Therefore, the objective of the present work is to investigate the vacuum brazing behaviour of Binder Jetting manufactured AISI 316L TPMS structures and hybrid joints combining additively manufactured and conventionally produced AISI 316L components. Three filler metals exhibiting fundamentally different joining mechanisms were evaluated: pure copper (BCu-1), characterized by highly capillary-driven flow; the nickel-based alloy BNi-2, which promotes diffusion-assisted bonding and spreading; and the active Ag-Cu-Ti alloy TiCuSil, whose wetting behaviour is governed by interfacial chemical reactions. Particular attention is devoted to wetting characteristics, capillary transport, interfacial microstructural evolution, and filler-metal migration within gyroid architectures. In addition to joint formation, the study explores the potential of vacuum brazing as a simultaneous joining and internal coating process for complex TPMS structures, providing new insights into the manufacturing and functionalization of advanced heat-exchanger components fabricated by Binder Jetting.

2. Materials and Experimental Procedure

2.1 Materials

Base material

The present study was focused on AISI 316L austenitic stainless steel. Two different material conditions were considered. The first condition corresponded to components manufactured by additive manufacturing using the Binder Jetting (BJ) process. The chemical composition of the feedstock powder employed for the fabrication of these components is presented in Table 1.

Element	wt.%
Carbon	0.021
Silicon	0.368

Manganese	1.039
Chromium	16.878
Molybdenum	2.198
Phosphorus	0.035
Sulphur	0.021
Nickel	10.724
Oxygen	0.082
Nitrogen	0.079
Iron	Balance

Table 1. Chemical composition of the AISI 316L powder used in the Binder Jetting process (wt.%).

Binder-jetted stainless steel components are increasingly being considered for structural and industrial applications. In many cases, these parts must be joined either to assemble larger and more complex geometries or to integrate conventionally manufactured components within hybrid structures.

To represent these industrial scenarios, the additively manufactured AISI 316L components were joined to conventionally produced AISI 316L tubes. The tubes had an external diameter of 20 mm and a wall thickness of 2 mm. This configuration enabled the evaluation of joints between additively manufactured and wrought materials, which is of particular interest for piping systems, fluid transport equipment and other industrial assemblies requiring dimensional flexibility and functional integration.

Prior to joining, the surfaces of all specimens were degreased to remove contaminants that could affect joint quality.

Filler metals

Three filler metals exhibiting distinctly different wetting, diffusion, and interfacial bonding mechanisms were selected in order to investigate the influence of filler-metal chemistry on joint formation and capillary-driven migration in Binder Jetting (BJ) AISI 316L components: pure copper (BCu-1), the nickel-based brazing alloy BNi-2, and the active Ag-Cu-Ti alloy TiCuSil. The nominal chemical compositions, standard classifications, melting ranges, and recommended brazing temperatures are summarized in Table 2.

Filler	Chemical Composition (% wt)	Liquidus (°C)	Solidus (°C)
BCu-1	Cu: 99.9 min	1085	1085
BNi-2	Ni: Bal, Cr: 7.0, B: 3.1, Si: 4.5, Fe: 3.0	970	1000
Ticusil®	Ag: 68.8, Cu: 26.7, Ti: 4.5	780	900

Table2 Filler metals selected for the study

The selection was intended to cover three different brazing behaviours. Pure copper is characterized by a single melting temperature (1085 °C) and extremely high fluidity under vacuum conditions, making it particularly suitable for evaluating capillary flow and filler-metal transport over rough surfaces. BNi-2 combines excellent wettability and flowability with diffusion-controlled bonding. During brazing, boron and silicon diffuse into the stainless-steel substrate, promoting isothermal solidification and the formation of a diffusion-affected zone (DAZ), while simultaneously influencing the extent of filler-metal spreading. In contrast, TiCuSil is an active brazing alloy whose joining mechanism relies on the presence of titanium, which reacts with the passive chromium oxide layer on stainless steel and promotes wetting through interfacial chemical reactions. As a result, its behaviour is generally more localized and less dependent on capillary flow than that of Cu or BNi-2.

The use of these three filler metals enables a direct comparison between highly capillary-driven flow (Cu), diffusion-assisted spreading (BNi-2), and reaction-controlled wetting (TiCuSil). This provides a suitable experimental framework for assessing how filler-metal chemistry affects both brazed joint formation and the development of internal coatings on complex gyroid structures manufactured by Binder Jetting.

2.2 Experimental configurations

In order to reproduce representative joining scenarios encountered in compact heat exchanger manufacturing, two experimental joint configurations were designed and evaluated. These geometrical arrangements were selected to emulate the spatial constraints and complex interfaces typically found in advanced thermal management systems incorporating additively manufactured components.

a. Tube-to-Structure Configuration

The first configuration consisted of the joining of two conventionally manufactured AISI 316L tubes to a Binder Jetting (BJ) fabricated component. Particular attention was paid to the relative positioning of the tubes, which were deliberately arranged with a minimum inter-tube spacing. This geometry was intended to reproduce the highly compact layouts commonly encountered in heat exchangers, where the close proximity between adjacent flow channels significantly restricts accessibility during welding operations and increases thermal interaction between neighbouring joints.

From a manufacturing perspective, this configuration represents a particularly challenging case due to the combined effects of geometric confinement, restricted torch accessibility, localized heat accumulation and potential thermal overlap between successive welds. Consequently, it provides a suitable framework for assessing the feasibility and robustness of joining additively manufactured components under realistic industrial conditions.

b. Gyroid-to-Plate Configuration

The second configuration consisted of the joining of a Binder Jetting manufactured gyroid structure to a flat AISI 316L plate. The gyroid architecture belongs to the family of Triply Periodic Minimal Surface (TPMS) lattices, which have attracted increasing attention for application in compact heat exchangers due to their high specific surface area, enhanced heat transfer capabilities and favorable stiffness-to-weight ratio.

This configuration was selected to represent encapsulated TPMS-based structures, where a cellular core must be integrated into an external shell or containment wall through a joining operation. Such assemblies are particularly relevant for advanced heat exchanger concepts fabricated by additive manufacturing, in which complex internal architectures cannot be produced using conventional manufacturing routes.

From a welding metallurgy standpoint, the gyroid-to-plate joint introduces additional challenges associated with the highly heterogeneous thermal mass distribution, variable local heat dissipation pathways and non-uniform stiffness of the lattice structure. These factors can strongly influence melt pool dynamics, heat flow patterns, solidification behaviour and residual stress development. Therefore, this configuration provides an appropriate experimental platform for investigating the interaction between joining process conditions and the structural features inherent to TPMS architectures.

2.3 Vacuum brazing procedures

All brazing experiments were carried out in a vacuum furnace under controlled thermal conditions. The brazing cycles were defined according to the melting characteristics, joining mechanisms, and processing requirements of each filler metal. BCu-1, BNi-2, and TiCuSil require significantly different thermal profiles owing to their distinct melting ranges, diffusion behaviour, and interfacial reaction mechanisms.

For BCu-1, brazing was performed at 1105 °C. Since copper exhibits a single melting temperature (1085 °C) and high fluidity under vacuum conditions, a partial pressure of 0.1 mbar was introduced above 750 °C to minimise copper evaporation and unwanted metal deposition within the furnace, figure 1. The process was designed to promote complete melting and capillary flow while maintaining dimensional stability of the components.

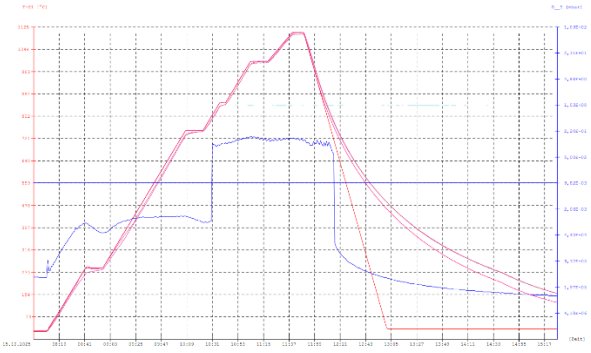


Figure 1. Temperature–time profile recorded during the vacuum brazing cycle of the BCu-1

The BNi-2 brazing cycle was conducted at 1050 °C. Because the alloy was applied as a brazing paste, an intermediate dwell at approximately 500 °C was included to ensure complete removal of the organic binder before melting of the filler metal, figure 2. The selected temperature provided sufficient fluidity and promoted diffusion of boron and silicon into the stainless-steel substrate, facilitating isothermal solidification and metallurgical bonding.

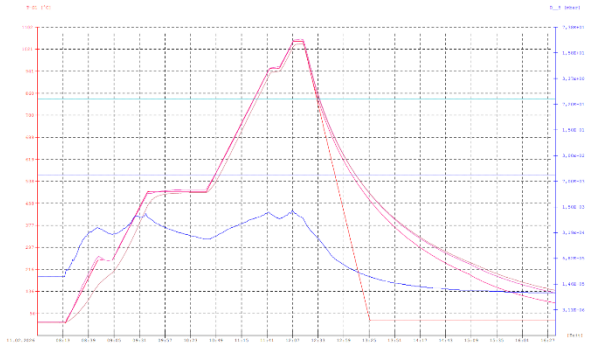


Figure 2. Thermal cycle applied during vacuum brazing of the AISI 316L components using BNi-2 filler metal.

TiCuSil joints were processed at 880 °C. Unlike BCu-1 and BNi-2, TiCuSil is an active brazing alloy whose joining mechanism relies primarily on interfacial reactions involving titanium. Therefore, complete filler-metal flow is not essential for successful bonding. The selected temperature enabled the formation of the active reaction layer while limiting excessive spreading of the filler metal, figure 3.

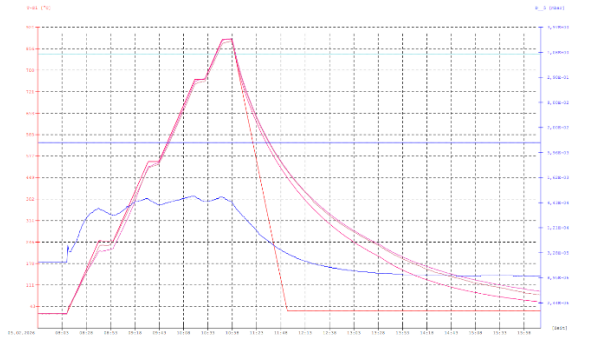


Figure 3 Temperature–time profile of the vacuum brazing cycle using Ticusil filler metal.

2.4 Characterization techniques

Following brazing, the assemblies were systematically characterized to evaluate joint integrity, filler-metal distribution, and the metallurgical phenomena occurring at the brazed interfaces. Visual inspection was initially conducted to assess wetting behaviour, filler-metal spreading, fillet and meniscus formation, as

well as the presence of visible defects such as incomplete filling, excessive flow, or local filler accumulation. Special attention was devoted to the uniformity of filler-metal distribution and the extent of capillary-assisted spreading within the joint region.

Macrographic analyses were subsequently performed on metallographically prepared cross-sections to examine joint continuity, gap filling, and filler-metal penetration.

Microstructural characterization was carried out by scanning electron microscopy (SEM) operating in high-vacuum mode at an accelerating voltage of 20 kV. SEM observations were used to investigate the morphology, continuity, and microstructural features of the brazed interfaces, including diffusion-affected regions, reaction layers, and solidification products. To complement the microstructural analysis, energy-dispersive X-ray spectroscopy (EDS) point analyses and line scans were performed across selected interfaces. These analyses enabled the identification of elemental distributions, compositional gradients, and diffusion phenomena between the filler metals and the AISI 316L substrates.

3. Results

The experimental program was designed to evaluate the influence of filler-metal chemistry on joint formation and filler-metal transport in Binder Jetting (BJ) AISI 316L structures. Different filler metals were selected for each joint configuration according to the specific phenomena under investigation. For the tube-to-structure assemblies, BCu-1 and BNi-2 were employed owing to their high fluidity and excellent wettability on stainless steel, which make them particularly suitable for assessing gap filling, capillary flow, and metallurgical bonding in confined joining geometries. In contrast, the gyroid-to-plate configuration was investigated using BNi-2 and TiCuSil. BNi-2 was selected because of its combined spreading and diffusion behaviour, whereas TiCuSil was included as an active brazing alloy exhibiting a more localized wetting mechanism governed by interfacial reactions. This experimental approach enabled the comparison of diffusion-assisted spreading and reaction-controlled wetting in complex TPMS architectures, while also providing insight into the potential for capillary-driven filler-metal migration and internal surface coating within gyroid structures.

3.1 Tube-to-structure joints

BCu-1 filler metal

Visual inspection revealed complete gap filling and a continuous joint, indicating adequate wetting and flow of the molten copper under the selected vacuum brazing conditions.

A notable difference was observed in the spreading behaviour of the filler metal on the two substrates. While the Binder Jetting (BJ) component exhibited extensive copper coverage beyond the immediate joint region, the conventional AISI 316L tube showed only localized wetting around the joint interface. This behaviour can be attributed to the substantially different surface characteristics of the two materials. The BJ component possesses a rough surface topography and residual porosity resulting from the sintering process, which promotes capillary-driven flow and the so-called wicking effect. Consequently, the molten copper was able to spread over the BJ surface, generating a diffuse and extended wetting front. In contrast, the wrought tube presents a comparatively smooth and dense surface with limited capillary pathways, restricting filler-metal migration and confining wetting to the vicinity of the joint, figure 4.



Figure 4. Differential wetting behavior of BCu-1 on Binder Jetting and wrought AISI 316L substrates.

These observations demonstrate that the manufacturing route has a significant influence on filler-metal transport during brazing. The enhanced capillary activity of the BJ material not only promotes joint formation but also favours the development of copper coatings on exposed surfaces, highlighting the potential of vacuum brazing as a combined joining and surface-functionalization process.

Sound brazed joints were successfully produced using the BCu-1 filler metal, with well-defined menisci formed on both sides of the joint. The macrograph reveals a continuous and homogeneous Cu-based brazed layer along the 316L/Binder Jetting interface, with effective wetting and filling of the joint gap. No macroscopic voids, cracks, or interfacial discontinuities are observed, while the Binder Jetting region exhibits a fine and uniformly distributed residual porosity characteristic of the sintered material. The joint geometry remains well defined, with no evidence of significant filler-metal depletion or excessive infiltration into the porous substrate, figure 5.

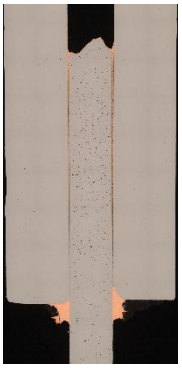


Figure 5, Cross-sectional macrograph of the tube-to-structure joint brazed using BCu-1 filler metal.

Figure 6 shows a representative SEM micrograph (500×) of the BCu-1 brazed joint. A continuous Cu/316L interface is observed on both the Binder Jetting (BJ) substrate and the conventionally manufactured tube, confirming effective wetting and sound joint formation. The irregular morphology at the lower interface reflects the characteristic roughness of the BJ material, while the upper tube interface remains comparatively smooth. No significant defects, discontinuities, or lack of bonding were observed along the joint region.

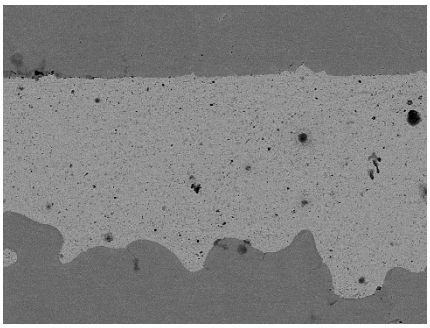


Figure 6. SEM micrograph of the Cu/316L brazed interface in the tube-to-structure assembly.

Figure 7 presents the EDS line-scan profile acquired across the Cu/316L brazed joint. A well-defined compositional transition is observed between the copper-rich brazing layer and the stainless-steel substrates. The central region is characterized by a strong Cu signal, while Fe, Cr and Ni intensities decrease significantly, confirming that the joint is predominantly composed of the BCu-1 filler metal. At both interfaces, a sharp increase in the Fe, Cr and Ni signals is detected together with a corresponding decrease in Cu intensity, indicating a relatively limited diffusion zone and the absence of extensive intermixing between copper and the AISI 316L substrates. The similar compositional evolution observed at both sides of the joint demonstrates effective metallurgical bonding to both the wrought tube and the Binder Jetting

component, in agreement with the continuous interfaces observed in the SEM micrograph. The local fluctuations in elemental intensity are attributed to the inherent roughness and heterogeneity of the BJ surface.

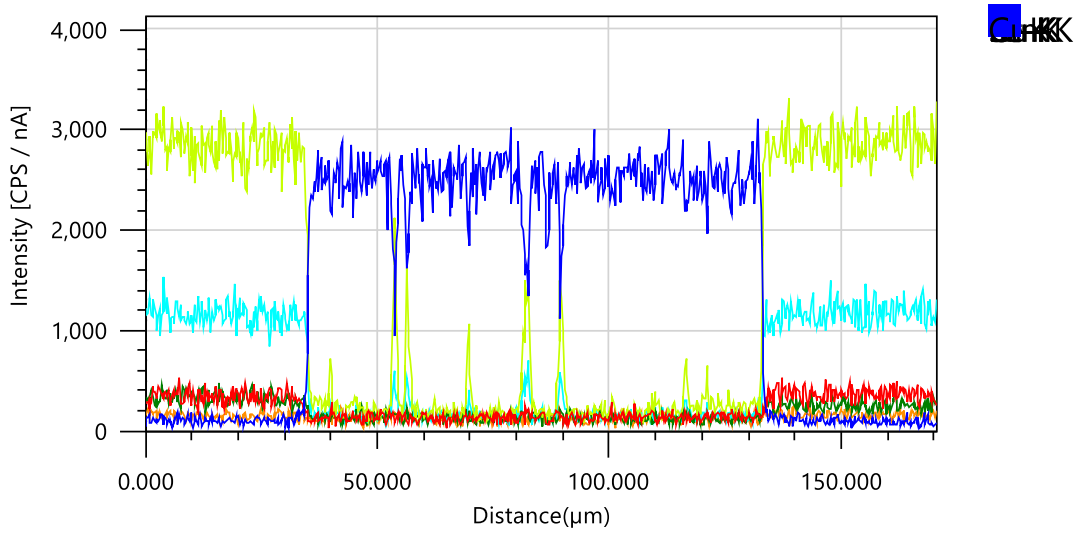


Figure 7 EDS elemental profile across the BCu-1 joint joining a Binder Jetting AISI 316L component to a wrought AISI 316L tube.

Visual inspection of the assemblies brazed with BNi-2 revealed the formation of continuous menisci on both sides of the joint, indicating excellent wettability and filler-metal flow during vacuum brazing. As shown in figure 8, the filler metal spread preferentially over the Binder Jetting (BJ) component, producing a visible metallic coating beyond the joint region, whereas wetting on the conventionally manufactured tube remained largely confined to the vicinity of the interface. Similar to the behavior observed with BCu-1, this preferential spreading is attributed to the rougher surface and residual porosity of the BJ material, which enhance capillary-driven flow through a pronounced wicking effect. However, unlike the copper filler metal, BNi-2 generated a more uniform and continuous surface coating while maintaining a well-defined joint geometry.



Figure 8. Macroscopic view of the tube-to-structure assembly brazed with BNi-2 showing meniscus formation and preferential filler-metal spreading on the Binder Jetting substrate.

Macrographic examination confirmed complete gap filling and the formation of continuous menisci on both sides of the joint.

The brazed region exhibits the characteristic solidification structure of BNi-2. Adjacent to the brazed region, diffusion-affected zones (DAZ) are visible on both sides of the interface, figure 9. These regions are associated with the diffusion of boron and silicon from the molten filler metal into the AISI 316L substrates and the resulting metallurgical interaction with the base material.

Overall, the macrographic observations demonstrate that BNi-2 provides not only complete joint formation but also significant metallurgical interaction with the substrate and simultaneous surface coating of the BJ component.

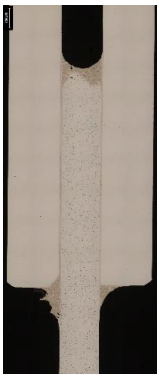


Figure 9. Macrographic cross-section of the BNi-2 brazed joint showing complete gap filling,

SEM examination of the BNi-2 brazed joint, acquired at 800× magnification, reveals a continuous bonding region between the AISI 316L substrates with no evidence of voids, cracking, or lack of filling. A diffusion-affected region is clearly visible on both sides of the joint, indicating significant metallurgical interaction between the Ni-based filler metal and the stainless-steel substrates, figure 10.

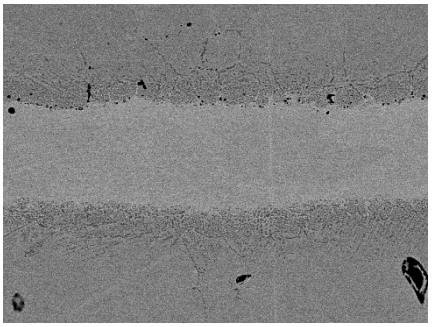


Figure 10 SEM micrograph of the BNi-2 brazed joint.

The EDS line-scan profile across the joint confirms this behaviour. Unlike the BCu-1 joint, where the compositional transition between the copper-rich filler and the stainless-steel substrates is relatively abrupt, the BNi-2 joint exhibits a gradual variation in elemental concentrations across the interfaces. The Ni signal progressively increases towards the centre of the joint, while the Fe and Cr signals decrease smoothly from the AISI 316L substrates into the brazed region. This compositional gradient is consistent with substantial interdiffusion between the filler metal and the base material during brazing, figure 11.

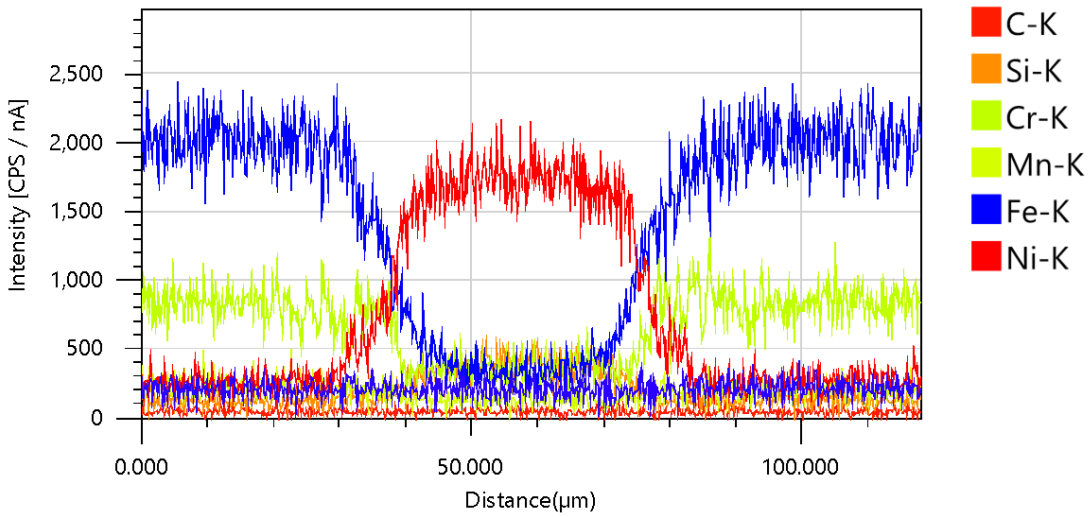


Figure 11 EDS line-scan across the BNi-2 brazed joint showing the distribution of Ni, Fe, Cr and other alloying elements across the brazed interface.

3.2 Gyroid-to-plate joints

Ticusil filler metal

In contrast to BNi-2, which promoted extensive filler-metal spreading and coating formation throughout the gyroid structure, TiCuSil exhibited a much more localized wetting behaviour. As shown in figure 12, the upper regions of the gyroid remained free of filler metal and retained the characteristic rough surface morphology produced by the Binder Jetting process. This observation indicates that the molten TiCuSil did not migrate significantly through the lattice structure and that no continuous internal coating was formed.

The restricted spreading behaviour can be attributed to the higher surface tension of the Ag-Cu-based filler metal and to the active brazing mechanism associated with titanium. Rather than relying primarily on capillary-driven transport, wetting is promoted through localized interfacial reactions between titanium and the surface oxides of the stainless steel. Consequently, filler-metal flow remained largely confined to the vicinity of the joint.

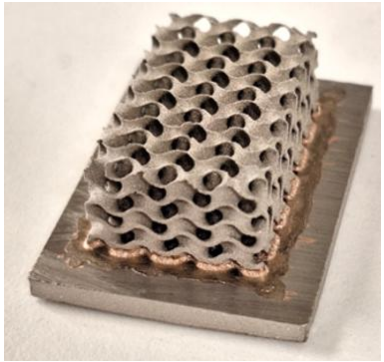


Figure 12 Gyroid-to-plate assembly brazed with TiCuSil showing localized wetting and the absence of extensive filler-metal spreading over the gyroid structure.

The cross-sectional micrograph shown in figure 13 confirms the formation of a sound joint between the gyroid and the substrate. Concave menisci are observed at the base of the gyroid struts, indicating effective wetting and filler accumulation at the joining interface. The metallurgical bond is therefore expected to be governed primarily by the formation of a thin titanium-rich reaction layer at the interface rather than by extensive diffusion into the AISI 316L substrate.

Overall, TiCuSil proved effective for producing localized and well-defined joints, while minimizing filler-metal migration through the gyroid structure. This behaviour may be advantageous in applications where preservation of rugosity and strict control of filler-metal distribution are required.

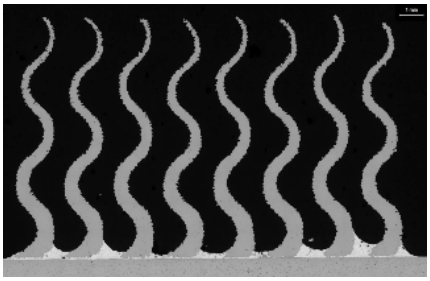


Figure 13 Cross-sectional micrograph of the TiCuSil-brazed gyroid-to-plate joint

SEM examination of the TiCuSil brazed joint (1000×) reveals the characteristic heterogeneous microstructure of Ag-Cu active brazing alloys. As shown in Figure X, the brazed region is composed of alternating Ag-rich and Cu-rich islands distributed throughout the joint. The EDS line-scan confirms this morphology through the oscillating Ag and Cu signals across the brazed seam, indicating phase separation during solidification, figure 14.

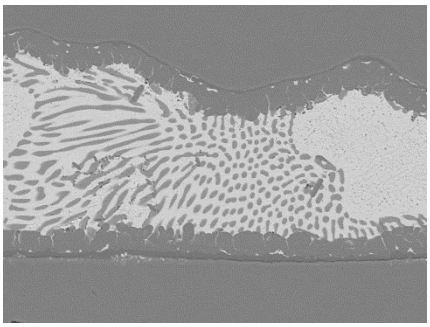


Figure 14. SEM micrograph of the TiCuSil brazed interface showing the Ag-Cu solidification structure and titanium-rich reaction layers at the AISI 316L interfaces.

The TiCuSil joint is characterized by localized interfacial reactions. The Ti signal exhibits pronounced peaks at both edges of the joint, demonstrating that titanium preferentially reacts at the interface with the AISI 316L substrate. Simultaneously, the Ag and Cu signals decrease significantly within these reaction regions, while a slight enrichment in Cr is observed. This behaviour suggests interaction between titanium and chromium-containing surface compounds, leading to the formation of a thin reaction layer responsible for metallurgical bonding, figure 15.

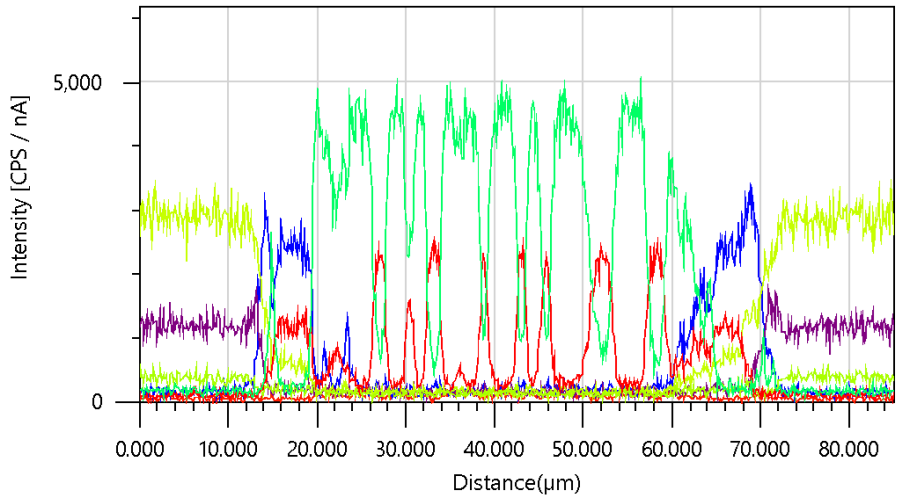


Figure 15. EDS line-scan across the TiCuSil brazed interface showing Ag-Cu phase distribution and Ti enrichment at the reaction layers.

BNi-2 filler metal

As shown in figure 16, the BNi-2 filler metal extensively spread throughout the gyroid structure, producing a nearly continuous metallic coating on all accessible surfaces. The characteristic rough texture of the Binder Jetting (BJ) material is largely masked by the deposited filler metal, indicating that capillary-driven transport occurred well beyond the initial joining region. This behaviour contrasts with that observed for TiCuSil, where filler-metal flow remained localized near the joint interface. The image clearly demonstrates that the interconnected TPMS architecture acts as an efficient capillary network, enabling the molten BNi-2 to migrate through the structure and coat internal and external surfaces while simultaneously forming the brazed joint**.**

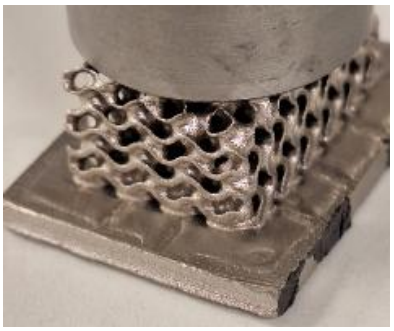


Figure 16 Gyroid-to-plate assembly brazed with BNi-2 showing extensive filler-metal migration and coating of the gyroid surfaces.

Macrographic examination of the cross-section (Figure 17) confirms extensive penetration of the BNi-2 filler metal throughout the gyroid structure. The metallic phase is not restricted to the gyroid-to-plate interface but is also present along the internal strut surfaces, indicating significant capillary-driven migration through the interconnected TPMS network. The originally rough Binder Jetting surface appears uniformly covered by the filler metal, demonstrating the strong wetting capability of BNi-2 on the additively manufactured substrate.

No significant discontinuities, voids, or lack-of-bond regions are observed at the gyroid-to-plate interface. The filler metal effectively bridges the contact area while simultaneously coating the surrounding gyroid surfaces.

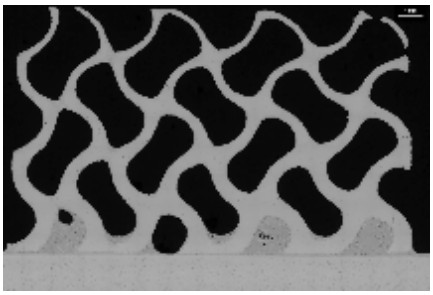


Figure 17. Macrographic cross-section of the BNi-2 brazed gyroid-to-plate assembly

3.3 Capillary-driven filler-metal migration and internal coating formation

One of the most significant findings of this work is the ability of vacuum brazing to generate metallic coatings on complex Binder Jetting (BJ) gyroid structures through spontaneous capillary-driven migration of the filler metal. While brazing is conventionally considered a joining process, the results demonstrate that, under suitable conditions, molten filler metals can be transported far beyond the primary joint region and deposited onto internal surfaces throughout the interconnected TPMS architecture.

Evidence of this phenomenon was observed in the plate-to-gyroid assemblies brazed with BNi-2. As shown in figure 18, the filler metal migrated through the gyroid network, coating virtually all exposed surfaces of the structure. The characteristic rough texture associated with the BJ process was largely masked by the deposited material, indicating that the molten alloy was able to spread well beyond the initial filler placement location.

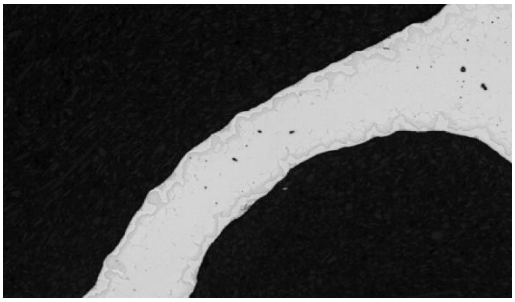


Figure 18. BNi-2 coated gyroid structure after vacuum brazing showing the formation of a continuous metallic layer on the strut surface.

In contrast, the as-built gyroid shown in figure 19 retains the irregular surface morphology generated during Binder Jetting and sintering, with no evidence of a continuous surface layer. The comparison between both conditions provides direct evidence of coating formation through capillary transport during brazing.

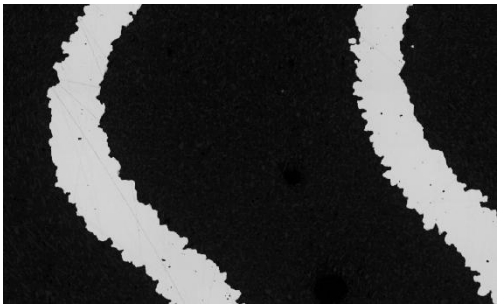


Figure 19 As-built Binder Jetting gyroid structure showing the characteristic rough surface morphology

To quantify the effect of coating formation, image-based roughness measurements were performed on gyroid struts before and after brazing with BNi-2. Twelve measurements were acquired for each condition. The as-built surface exhibited an average roughness of Rz = 89 ± 26 μm, whereas the coated condition

showed a significantly reduced value of Rz = 37 ± 11 μm. This reduction confirms that the molten filler metal partially fills surface asperities and smooths the rough topography characteristic of additive manufacturing parts.

The metallographic comparison further supports this interpretation. The uncoated gyroid exhibits the irregular profile associated with partially sintered particles and layer-by-layer fabrication, whereas the coated condition presents a continuous metallic layer surrounding the struts and following the local geometry of the TPMS structure. The coating appears adherent and relatively uniform, confirming that BNi-2 can effectively wet and cover complex internal surfaces by capillary action.

This result is particularly relevant because most conventional roughness-reduction techniques are based on material removal and are difficult to apply to complex gyroid structures, especially when access to internal surfaces is restricted. Common approaches such as machining and mechanical polishing, abrasive finishing methods, and chemical treatments including electropolishing may be unsuitable for thin-walled TPMS architectures, where dimensional accuracy and structural integrity must be preserved. In contrast, the brazing-based approach acts as an additive surface modification process, reducing roughness while simultaneously preserving the geometry and generating a metallic coating on otherwise inaccessible internal surfaces.

4. Discussion

The results demonstrate that the behaviour of filler metals during vacuum brazing of Binder Jetting (BJ) AISI 316L components is governed not only by filler-metal chemistry but also by the unique surface characteristics of the BJ material. Unlike conventionally manufactured stainless-steel substrates, BJ components exhibit a rough surface morphology and residual interconnected porosity resulting from the powder-based manufacturing route. These features create an effective capillary network that significantly influences filler-metal transport, wetting behaviour, and ultimately joint formation.

4.1 Influence of filler-metal chemistry on joint formation

The three filler metals investigated exhibited markedly different joining mechanisms. BCu-1 produced sound joints characterized by excellent wetting and complete gap filling. However, the EDS profiles revealed relatively abrupt compositional transitions between the copper-rich brazing layer and the stainless-steel substrates, indicating limited elemental interdiffusion. Consequently, joint formation was primarily governed by wetting and capillary flow rather than by extensive metallurgical interaction.

In contrast, BNi-2 combined excellent flowability with significant metallurgical interaction. The presence of diffusion-affected zones adjacent to the interfaces and the gradual compositional transitions observed in the EDS line scans demonstrate that diffusion played an active role during bonding. Such behaviour is characteristic of Ni-B-Si filler metals and is generally associated with improved metallurgical continuity between the filler metal and the substrate.

TiCuSil exhibited a fundamentally different behaviour. Filler-metal spreading remained localized near the joint region and bonding was dominated by interfacial reactions involving titanium. SEM and EDS analyses showed titanium enrichment at the joint interfaces together with local depletion of Ag and Cu, supporting the existence of reaction layers responsible for bonding. Unlike BNi-2, no extended diffusion-affected region was observed, indicating that joint formation was controlled predominantly by localized chemical reactions rather than long-range elemental diffusion.

These observations highlight the existence of three distinct joining mechanisms: capillary-driven bonding for BCu-1, diffusion-assisted bonding for BNi-2, and reaction-controlled bonding for TiCuSil. Understanding the relationship between filler-metal chemistry and transport behaviour is essential for the design of reliable brazed assemblies involving additively manufactured components.

4.2 Role of binder jetting surface morphology

A particularly relevant finding is the strong influence of the Binder Jetting surface condition on filler-metal flow. In both the tube-to-structure and gyroid-to-plate configurations, filler metals exhibited considerably greater spreading on the BJ substrates than on the wrought AISI 316L surfaces.

This behaviour is attributed to the combined effect of surface roughness and residual sintering porosity, which generate numerous capillary pathways capable of transporting molten filler metal. The phenomenon resembles the classical *wicking effect* frequently observed in porous materials, although in this case it occurs on metallic additively manufactured surfaces. The effect was especially evident for BCu-1 and BNi-2, which spread extensively across the BJ surfaces while remaining relatively confined on the conventionally manufactured substrates.

From a joining perspective, excessive capillary transport may be undesirable because it can deplete the joint of filler metal if the available volume is insufficient. However, the same mechanism can be exploited to deposit metallic layers on complex surfaces. Therefore, the capillary activity of BJ structures should not be regarded solely as a manufacturing challenge but also as a potentially useful feature for advanced surface engineering applications.

4.3 Vacuum brazing as a simultaneous joining and coating process

The most innovative result of the present study is the demonstration that vacuum brazing can simultaneously operate as a joining and coating process for complex Binder Jetting TPMS structures.

The gyroid experiments revealed that BNi-2 was capable of migrating through the interconnected lattice and coating surfaces located far from the original filler-metal placement. The comparison between coated and uncoated gyroids clearly showed that the deposited metallic layer significantly modified the surface morphology of the structure. Quantitative measurements confirmed this effect, with the average roughness decreasing from $Rz = 89 \pm 26$ μm in the as-built condition to $Rz = 37 \pm 11$ μm after coating.

The extensive migration of BNi-2 observed in the gyroid structures is consistent with transport mechanisms commonly observed in Binder Jetting systems, where liquid phases can propagate through interconnected particle networks by means of capillary action and infiltration phenomena. The combination of surface roughness and complex geometrical pathways promotes liquid transport over distances significantly larger than the initial deposition zone, favoring the redistribution of molten material throughout networks.

This reduction is particularly important because conventional roughness-reduction techniques are generally based on material removal. Processes such as machining, grinding, polishing, abrasive blasting, or electropolishing are often difficult or impossible to apply uniformly to enclosed TPMS geometries. Furthermore, excessive material removal may alter wall thickness, modify local geometries, and compromise the structural integrity of thin lattice elements.

In contrast, the brazing-based approach functions as an additive surface-modification process. Rather than removing material, the molten filler metal fills valleys and asperities generated during powder consolidation, thereby smoothing the surface while preserving the overall geometry of the structure. More importantly, the process is capable of reaching internal surfaces that are inaccessible to conventional finishing technologies.

This capability is particularly attractive for heat-exchanger applications. Surface roughness plays an important role in determining pressure losses, boundary-layer development, and fouling behavior within internal channels. The observed smoothing effect may therefore contribute to improved hydraulic performance while simultaneously providing a metallurgically bonded coating.

4.4 Implications for TPMS heat exchangers and future development

The investigated joining strategy addresses one of the main manufacturing limitations of complex TPMS heat exchangers produced by binder jetting additive manufacturing. Instead of fabricating enclosed components as monolithic structures, the geometry can be manufactured as open, sinter-friendly subcomponents and subsequently assembled by vacuum brazing. This approach reduces manufacturing

constraints while enabling the production of internal channels and architectures that would be difficult to realize through conventional routes.

Beyond joining, the results suggest a new application of brazing technology as a method for the functionalization of internal surfaces. By selecting an appropriate filler metal, it becomes possible to tailor the balance between joint formation and coating generation. BNi-2 promotes extensive migration and coating, whereas TiCuSil provides localized bonding with minimal filler redistribution. This flexibility offers new opportunities for the design of multifunctional heat-exchanger components in which structural joining and surface engineering are achieved simultaneously during a single thermal cycle.

Although further work is required to quantify coating thickness, migration distance, and long-term performance, the results provide strong evidence that capillary-driven filler-metal transport can be exploited as a manufacturing tool rather than regarded solely as a secondary effect of brazing. Consequently, vacuum brazing emerges not only as a joining technology for Binder Jetting components, but also as a promising route for the modification of otherwise inaccessible internal surfaces in advanced TPMS architectures.

5. Conclusions

This study investigated the vacuum brazing behaviour of Binder Jetting (BJ) manufactured AISI 316L structures using three filler metals with fundamentally different joining mechanisms: pure copper (BCu-1), the Ni-based alloy BNi-2, and the active Ag-Cu-Ti alloy TiCuSil. Particular attention was devoted to wetting behaviour, filler-metal transport, interfacial microstructural development, and the feasibility of using vacuum brazing for the assembly of complex TPMS architectures and internal-channel components. Based on the experimental results, the following conclusions can be drawn:

- Vacuum brazing proved to be an effective manufacturing route for assembling Binder Jetting AISI 316L components, enabling the fabrication of complex geometries that would be difficult or impractical to produce as monolithic structures. The proposed strategy of manufacturing open BJ subcomponents followed by brazed assembly offers a practical solution for structures containing enclosed channels and highly interconnected architectures.
- The behaviour of the filler metal was strongly dependent on its chemistry and joining mechanism. BCu-1 produced excellent wetting and complete gap filling, with bonding primarily governed by capillary flow and limited elemental interdiffusion. BNi-2 promoted significant metallurgical interaction through diffusion-assisted bonding, while TiCuSil generated localized joints controlled by titanium-driven interfacial reactions.
- The surface characteristics of the Binder Jetting material had a major influence on filler-metal transport. Compared with conventionally manufactured AISI 316L, the BJ substrates exhibited substantially greater spreading of the molten filler metals due to the combined effects of surface roughness, which created effective capillary pathways for liquid transport.
- For tube-to-structure assemblies, both BCu-1 and BNi-2 produced sound joints with complete gap filling and good metallurgical integrity. However, BNi-2 generated a diffusion-affected zone and a more gradual compositional transition across the interface, indicating stronger metallurgical continuity between filler metal and substrate.
- TiCuSil exhibited highly localized wetting behaviour in the gyroid-to-plate configuration. Filler-metal migration remained confined to the vicinity of the joint and bonding was dominated by the formation of titanium-rich reaction layers at the AISI 316L interface. This behaviour minimizes filler redistribution and may be advantageous in applications requiring strict control of filler-metal location.
- BNi-2 exhibited extensive capillary-driven migration through the interconnected gyroid architecture. The molten filler metal propagated throughout the TPMS network, coating internal and external surfaces located far from the original filler-metal placement region. This demonstrates that Binder Jetting structures can act as efficient capillary networks during vacuum brazing.
- The BNi-2 migration mechanism enabled the simultaneous formation of a metallurgical joint and a continuous metallic coating on complex gyroid structures. Surface roughness measurements

showed a significant reduction from Rz = 89 ± 26 μm in the as-built condition to Rz = 37 ± 11 μm after brazing, confirming the capability of the molten filler metal to smooth the surface by filling valleys and asperities without altering the overall geometry.

- The results demonstrate that vacuum brazing should not be regarded solely as a joining technology for Binder Jetting components. Under suitable conditions, it can also function as an additive surface-engineering process capable of modifying internal surfaces that are inaccessible to conventional finishing techniques.
- The proposed approach is particularly attractive for TPMS-based heat exchangers and advanced thermal-management systems. By combining assembly and internal surface functionalization in a single thermal cycle, vacuum brazing expands the manufacturing possibilities of Binder Jetting and provides a viable route for producing multifunctional components with complex internal architectures.

Overall, the present work demonstrates that filler-metal chemistry governs not only joint formation but also the extent of capillary-driven transport within Binder Jetting structures. The ability to tailor the balance between localized bonding and extensive internal coating formation offers new opportunities for the manufacture and functionalization of advanced TPMS components and compact heat exchangers.

Author contribution

B. Arregi: Conceptualization, Methodology, Investigation, Experimental Work, Formal Analysis, Visualization, Writing (Original Draft). I. Dávila: Binder Jetting manufacturing of gyroid structures, Methodology, Writing (Review & Editing). G. Atxaga: Conceptualization, Supervision, Resources, Project Administration, Writing (Review & Editing).

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Declarations

Competing interests The authors declare no competing interests.

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