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Bond Strength Measurement for Additively Manufactured Inconel 718- GRCop84 Copper Alloy Bimetallic Joints

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Abstract

To benefit from the fascinating properties of multi-material structures, the interfacial joint should exhibit good mechanical strength. Evaluating the shear strength of a bimetallic joint via conventional methods is usually complex, and in most cases produces unreliable data due to induced bending stress among others. In this work, a novel single-shear test device was designed and fabricated to measure shear strength of bimetallic joints. The device was first standardized by shearing standard materials, and the results were in good agreement with published data. Subsequently, the shear strength of Inconel 718/copper alloy (GRCop-84) bimetallic joint built via laser engineered net shaping (LENSTM) was evaluated. Compression test on the bimetallic joint was carried out as well for mechanical characterization. Both shear and compressive yield strengths of bimetallic joints were compared with the base materials in addition to influence of thermal cycling on the joint strength. Inconel 718/GRCop-84 bimetallic-joint shear strength was 220 ± 18 MPa and 231 ± 27 MPa for as-printed sample and after thermal cycling, respectively. Likewise, the bimetallic yield strength after compression test was 232 ± 3 MPa and 337 ± 15 MPa. No cracking through or along the interface was observed even after thermal cycling, which indicates no thermal degradation at the bimetallic interfacial joint. Increase in compressive yield strength after thermal cycling could be attributed to precipitation of Cr₂Nb particles in GRCop-84 matrix along with strengthening due to gamma phases in Inconel 718. Scanning electron microscopy (SEM) and backscatter electron imaging were used to examine the interfacial microstructures and failure modes. EDS was used as well to analyze the interface elemental composition. The development of the single-shear test device can provide an added opportunity to effectively evaluate mechanical behavior, reliability and performance of additively manufactured multi-material structures through bond strength analysis.

Keywords

LENSTM; Bimetallic structures; Joint-strength; Inconel 718; GRCop-84

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1. Introduction

Advanced composite materials possess unique properties suitable for various high-tech applications. Of various composite materials, bimetallic structures comprise two dissimilar metals joined together via different processes. They are principally developed either to benefit from the distinct properties of the base materials or to selectively improve the overall performance of one of the components [1]. Bimetallic structures have found a wide range of applications in aerospace industry through thermal barrier protection [2] and high thermal conductivity in gas turbine and rocket engines [3]. Other areas include automobile [4] and biomedical [5,6] industries for coatings to improve wear resistance on worn shafts and articulated joints, respectively. Conventionally, bimetallic structures are manufactured through fusion processes such as electron beam or laser welding [7, 8], brazing [9,10], friction stir welding [11, 12] and diffusion bonding [13, 14]. But, these processes involve multi-stage production, complex system set-up, long lead-time and high processing cost. Other disadvantages are porosity inclusion at the interfacial joint and structural distortion owing to high heat affected zone (HAZ). In recent years, additive manufacturing (AM) is used for processing multi-material structures to mitigate the challenges associated with various joining methods. Of various AM processes, directed energy deposition (DED) based system such as laser engineered net shaping (LENS™) is ideally suited for multi-materials manufacturing with varying compositions and functionalities. LENS can fabricate bimetallic structures via direct bonding [15], compositional gradation [16, 17] or using intermediate bond layer [18–20] for immiscible materials.

To evaluate mechanical behavior of bimetallic structures, measurement of metallurgical bonding at the interface is essential. Dissimilar metals with compatible metallurgical properties can form a single-phase solid-solution leading to a homogenized microstructure at the bimetallic interface and improve bond strength. Meanwhile, mismatch on the base-materials' metallurgical/thermal properties influence the bonding mechanics, and the interfacial bond strength of a bimetallic joint. The inherent challenges in dissimilar metal bonding like formation of brittle intermetallic phases resulting from weak interatomic-bonding lowers bimetallic joint strength. Likewise, wide difference in coefficient of thermal expansion (CTE) induces thermal/residual stresses at the interface of bimetallic joint. The presence of these stresses promotes crack initiation/propagation and lower bimetallic interfacial bond strength as well. It is important to examine interfacial bond strength of bimetallic structures to mechanically assess the reliability of the joint for structural performance. Generally, several test methods ranging from tensile, compressive and shear loading can be applied. Among these methods, shear strength at the interface of bimetallic joints have rarely been studied. This is because, only a single plane of shear is required at the interfacial bond-line. However, conventional single-shear process introduces bending stress on material structure during single-shear operation owing to the design configuration of the shear-device. Therefore, an impure shear is induced at the plane of interest, unlike double shear process which is simple and produces pure shear. However, double shear test is not suitable for testing interfacial shear strength of bimetallic joint due to simultaneous shearing of two regions - the interface region along with another region that is of no interest.

Among various conventional single-shear test techniques, a method employed by most researchers for testing interfacial shear strength of bimetallic structures is the ASTM D1002–99 Standard Test Method. This method is mostly appropriate for evaluating bond or shear strength of various adhesives/glues on metal, and not suitable for high shear strength in solidified metal-to-metal bonding. In most cases, bending, necking or tearing of the base material before/around the bond region were introduced when using this method, leading to erroneous results. Uscinowicz [21] showed such phenomenon on a single-lap Aluminum/Copper bimetallic joint while studying impact of temperature on shear strength. On a different technique, Pouranvari et al. [22] used a modified single-shear test device like the system utilized by Park et al. [23]. A sleeve tube was incorporated into their device to minimize bending effect on the specimen. However, a compromise to bending stress introduced excess shear force that ‘practically’ affected resultant shear strength. Thus, it became imperative that a single-shear test device is needed that is appropriate for testing interfacial shear strength of bimetallic joints.

In this work, we have designed and developed a single-shear test device that is suitable for testing shear strength of multi-material joints. For example, a bimetallic structure with one joint or a three-component structure with two joints. Functionality check was carried out on the device using standard single-materials: stainless steel (SS316L), Brass 360 and aluminum (Al 6061-T6), alongside bimetallic joints of Inconel 718/GRCop-84. INCONEL® 718, a nickel-based superalloy, is high-strength, corrosion-resistant material. Its main chemical compositions by wt % are: 52% Ni, 19% Fe, 18% Cr, 5% (Nb+Ta), 3-Mo, and traces of other elements. This material is widely used, especially in gas turbine and rocket engines because of its excellent mechanical properties such as high strength and excellent oxidation as well as fatigue resistance at elevated temperatures [24]. However, Inconel 718 show low thermal conductivity. Meanwhile, GRCop-84 is a copper-based alloy containing by wt%: ~88% Cu, 6.5% Cr and 5.8% Nb. The GRCop-84 alloy was developed at NASA for main combustion chamber (MCC) liners in the regeneratively cooled rocket engines because of its high thermal conductivity among other properties [25] but has low elevated temperature strength. A bimetallic joint of the two alloys was needed to benefit, distinctly, from various properties. Previous work via conventional manufacturing processes to fabricate bimetallic joint containing GRCop-84 proved difficult, including formation of microcracks and splat boundaries [26]. Therefore, laser engineered net shaping (LENS™), a commercially available additive manufacturing technique was used. Further discussion on LENS processing and the importance of the bimetallic structure can be found on Ref. [3]. The interfacial strength of the bimetallic joint was evaluated, and the results compared with the base materials. In addition, compression tests were performed on the bimetallic joints. Influence of thermal degradation on interfacial joint strength was examined with Inconel 718 and GRCop-84 materials. The development of the single-shear test device can provide an added opportunity to effectively evaluate mechanical behaviors, reliability and performance of additively manufactured multi-material joints through bond strength analysis.

2. Experimental procedures

A novel single-shear test device was designed and fabricated to evaluate the interfacial bond strength of bimetallic joints. With this fixture, the bond-line of a bimetallic sample can be

subjected to pure shear. Both single material and bimetallic joint were tested with the device. Compression testing was used as well with bimetallic joints.

2.1 Design and calibration of the shear device:

Fig. 1 shows the shear device assembly. A cold-rolled steel (AISI 1018) material was cut and machined to shape as pairs of shear-plates or load-arms with dimension $177\text{mm} \times 92\text{mm} \times 12.5\text{ mm}$ thick at shear section. Six (6) guide-slots were milled into one of the load-arm, while the other load-arm has six (6) drilled-holes to accommodate alloy steel shoulder-screws (Rockwell C32) comparable to Grade 8 steel. Both load-arms have shear-holes of hardened steel bushing inserts (Rockwell C61) with internal diameters approx. 3.1 mm and 4.7 mm. Other special fixtures of the device were: a pair of roller-plates, end-plates with adjusting screws and extensometer. The roller-plates eliminate bending stress induced on the test material, while the end-plates with adjusting screws permit accurate positioning of the bimetallic bond-line on the device's shear-plane. The extensometer measures the sample's displacement and eliminates machine compliance. After fabrication, the shear device was mounted on an Instron servo hydraulic testing machine (600DXS, Grove City, Pennsylvania) with Revere load-cell of 13.35kN at cross-head speed of 0.3mm/min. During shear testing, the slotted load-arm moves relative to the roller-plates secured with alloy steel shoulder-screws to the other load-arm, while the opposing sliding surfaces of the load-arms were lubricated to lower friction. The device was calibrated with standard single-material rods: stainless steel 316L, brass (360) and aluminum 6061-T6. The shear load-displacement curve generated were used to compute the shear strength of the materials and compared with published data. The frictional force on the shear-plates' sliding surfaces was measured without load and accounted for during shear strength calculation.

2.2 Additive manufacturing of bimetallic samples and bond strength test methods:

Additively manufactured Inconel 718/GRCop-84 bimetallic samples were fabricated via laser engineered net shaping (LENSTM) process. Initially, Inconel 718 material, about 14mm diameter and 7mm height was deposited on its substrate. Subsequently, GRCop-84 material was deposited on top of the Inconel 718 to form the bimetallic structure with overall height of ~ 12mm. Further details of the LENS processing parameters for the build is shown in Table 1.

Bimetallic samples were cut via waterjet and machined into 8mm length of 3mm and 4mm diameters. Three specimen-set from 3mm and 4mm diameters were heat-treated through a thermal cycle process for about 100 h (10 cycles). Heating rate was 10°C/min, 10hrs hold time at 500°C and cooled to 200°C at 10°C/min. The 3mm diameter specimens, both as-printed and after thermal cycling, were sheared using the 3.1mm shear-hole in the device. The position of interfacial bond-line on the specimens were measured and adjusted accordingly, using the adjustable screws on the end-plates, to align with the device's shear-plane. Likewise, Inconel 718 and GRCop-84 samples were sheared as well. The 4mm diameter specimens, both as-printed and after thermal cycling, were subjected to compression testing using a Shimadzu compression testing machine (AG-15, Kyoto, Japan) at a cross-head speed of 0.33mm/min. Similarly, pure Inconel 718 and GRCop-84 samples of the same dimensions were tested in compression as well. All tests were performed at

room temperature. Of the bimetallic samples tested in compression, selected specimens were sectioned perpendicular to the bond-line, Cross-sectional surfaces ground with silicon carbide (SiC) grinding paper and polished to 0.05 μ m using alumina-DI water suspension. Scanning electron microscopy (SEM) (FEI-SIRION, Portland, OR) was performed on the polished surfaces including the sheared samples. The microstructural features of the fractured surfaces, failure modes and deformation around the bond region were examined. Energy dispersive spectroscopy (EDS) was performed to generate elemental dot maps of the constituent elements at the interfacial region.

3. Results

During standardization of the single-shear test device for data reliability, preliminary shear strength results from SS316L, brass (360) and Al 6061-T6 rods were measured as 682 MPa, 294 MPa and 226 MPa, respectively. These results were in good agreement with published data as 669 MPa, 276 MPa and 207MPa in the same order, as shown in Fig. 2a. The shear plane of the bimetallic joints including the base materials are also shown in Fig. 2b. Other results including compression test are shown and explained further in this section.

3.1. Shear-zone:

Metallic materials' shear properties are measured through two different techniques, torsion or direct shear. For direct shear, understanding of shear mechanics within the shear-zone is essential. Fig. 3a and b illustrates the underlining principles in material deformation during shear operation. Fundamentally, single-material structures shear along the slip directions through dislocation motions that bring about plastic deformation. However, bimetallic-joint shear-zone is non-homogenous, i.e., the zone comprises the interfacial reaction region with inclusion of base materials, as shown in Fig. 3c. For this reason, exerting pure shear stress along the bimetallic interface or bond-line is always challenging. Though, with precision measurement, shearing through the bond-line was achieved using this device.

3.2. Bimetallic-joint strength and interfacial microstructure:

Fig. 4 shows the shear stress vs normalized displacement (ratio of material's displacement to the diameter) curves for LENS processed Inconel 718 and GRCop-84 specimens including the bimetallic interfacial-joints for as-printed samples and after thermal cycling condition. Similarly, Fig. 5 shows shear strength for these samples with Inconel 718 having the highest value 653 ± 11 MPa, followed by the bimetallic joints with 220 ± 18 MPa and 231 ± 27 MPa for as-printed and after thermal cycling, respectively, and the lowest was GRCop-84 with 110 ± 5 MPa. Inconel 718 shear strength obtained was low compared to published data, 703 MPa [27] due to no post process heat-treatment. The increase in shear strength of the bimetallic joints over GRCop-84 was indicative of good metallurgical bonding at the interface attributed to formation of a single-phase solid-solution of Ni-Cu. However, no significant difference in shear strength was observed between as-printed bimetallic joint and after thermal cycling, which indicated no effect of thermal degradation on the bimetallic interfacial joint. Fig. 6 shows the SEM images of microstructural features of all sheared surfaces. At higher magnification, the fractography of Inconel 718 shown in Fig. 6a reveals fine dimples, a characteristic feature of ductile fracture. Similarly, in Fig. 6b, cleavage and

ridges, including voids and porosities were observed in GRCop-84 fractography. These features resemble a failure mode for a typical brittle material. The bimetallic joint's fractography shown in Fig. 6c resembles combined brittle-ductile failure mode attributed to an interactive fracture characteristic of Inconel 718 and GRCop-84. It is not uncommon for bimetallic joint to show combined failure features of the parent materials, owing to good metallurgical bonding or formation of a new phase that can exhibit such characteristics. Meanwhile, Fig. 7 compares the microstructural features and failure modes of the sheared interfacial joints for as-printed bimetallic samples and after thermal cycling. The fractography in Fig. 7a shows flat islands which suggests failure initiated from the interfacial boundary. In contrast, Fig. 7b shows coarse grains with unstructured failure pattern including agglomerated white precipitates of Cr₂Nb, observed at high magnification.

Fig. 8 shows samples of Inconel 718, GRCop-84 and the bimetallic joint before and after compression test. Inconel 718 exhibited ductile deformation according to maximum shear stress theory, while GRCop-84 failed by shear fracture on a plane 45 degrees to the compression axis. However, the bimetallic joint fracture mode was mostly 'crushing' (deformation without unique pattern) of the copper alloy section. Fig. 9 shows the stress-strain curves of these specimens including the bimetallic joint after thermal cycling. Inconel 718 samples exhibit distinct elastic and plastic deformation zones during the test compared to GRCop-84. There was an improvement in the stiffness of the bimetallic joint after thermal cycling compared to the as-printed condition. The 0.2% yield strength (YS) and elastic modulus (EM) of all samples are shown in Fig. 10. Inconel 718 YS was 712 ± 38 MPa compared to 650 MPa reported by Blackwell [28]. However, the YS of GRCop-84 was 162 ± 11 MPa in comparison to 225.6 MPa reported in literature [25] for as-rolled material. However, the bimetallic joints YS were 232 ± 3 MPa and 337 ± 15 MPa for as-printed and after thermal cycling, respectively. These values were higher than GRCop-84 YS which was expected due to combined effect of Inconel 718 with the copper alloy. The low YS of LENS processed GRCop-84 compared to literature needs further scientific understanding. The reasons for the improved YS of the bimetallic joint after thermal cycling is attributed to precipitation of gamma strengthening phases in Inconel 718 matrix and precipitation hardening of the copper-chromium alloy.

Fig. 11 shows the backscattered electron images of the bimetallic joint cross sections. It compares the interfacial deformation features before and after compression test including after thermal cycling. No evidence of cracking was observed at the interface even at high magnification. These results suggest improved interfacial bond strength after compression test. Meanwhile, micropores and voids were observed including severe crushing failure at the upper section of the interface, as shown in Fig. 11c. This was due to increased brittle behavior GRCop-84 after thermal cycling. In Fig. 12, the EDS analysis on the bimetallic joint cross-section shows elemental diffusion of Ni and Fe including agglomeration of Cr-Nb particles along the interface which correlated with the white deposits seen in Fig. 11. These test results are presented in Table 2, and it shows that shear strength of the bimetallic joints increased by just 5%, while compressive yield strength increased by approximately 45% after thermal cycling.

4. Discussion

Mechanical reliability of a bimetallic structure depends not only on the method of processing and conditions, but most importantly on the interfacial-joint characteristics, especially the bond strength alongside interfacial microstructures. Since Inconel 718 and GRCo-84 are used in areas of high temperature applications where thermal cycling is prevalent, the influence of thermal degradation on mechanical properties of the bimetallic joint was equally important and examined. The two test methods, shear and compression, used to evaluate the bond strength of Inconel 718/GRCo-84 bimetallic joint fabricated via LENSTM showed characteristic similarities. In principle, bimetallic joint shear strength analysis is complex, first, it requires a single-shear process through the bond-line; and second, heterogeneity of the materials within the bimetallic joint shear-zone hinders some other aspects of characterization. Through the incorporation of special fixtures like roller-plates, end-plates with adjusting screws as well as extensometer to further enhance performance of the device, shearing at the bimetallic interfacial joint was achievable, and results proved reliable.

An analogy to the bimetallic shear-zone in Fig. 3c is the shear punch test (SPT) technique [29] used for small test samples to evaluate mechanical properties, especially, yield and ultimate strength of materials. For the bimetallic shear-zone model, good tolerance is required to exactly shear at the bond-line. In fact, without precise positioning of the interfacial bond-line on the device's shear plane, some parts of the bimetallic structure will deform internally within the shear-hole, giving an erroneous result. As illustrated in Fig. 3c, shear strength ($\tau_{\max}$) of the bimetallic joint through the bond-line was obtained as the ratio of maximum shear force ($F_{\max}$) before failure/fracture to initial area (A_{int}) of the sample, i.e., $\tau_{\max} = F_{\max}/A_{\text{int}}$, where A_{int} is $\pi(d/2)^2$. Other deformation parameters at the shear-zone include material's displacement (δ), shear strain angle (ϕ) and clearance (c). Shear strain (γ) is equal to $\tan(\phi) = \delta/c$ for small angle, ϕ . In practice, clearance (c) is usually very small leading to high shear strain induced on material at the shear-plane. If material deforms within the shear-hole during shear operation as shown in Fig. 3a, it becomes difficult to accurately compute the shear-strain, and this affects proper estimation of material's shear modulus using this approach, even with shear stress-normalized displacement criterion [30].

Based on the shear and compression test results, some parallels could be drawn between the base-materials' strengths and the bimetallic joints. Inconel 718 and GRCo-84 samples served as controls to establish base-line strength for the bimetallic joint. From the shear test, shear strength of Inconel 718 was much higher than that of GRCo-84, and the bimetallic interfacial-joint shear strength, ~220 MPa, was approximately 100% higher than GRCo-84 as well. Such an improved interfacial bond strength is needed to ensure mechanical reliability of the joint and can be attributed to the formation of a single-phase solid-solution of Ni-Cu as reported elsewhere [3]. Elemental diffusion and accumulation of particles around the interfacial region could as well influence the bond strength. The precipitation of Cr₂Nb particles has been reported even after conventional manufacturing of GRCo-84 with finely dispersed large volume fractions [25] within the copper alloy matrix. The shear strength of additively manufactured bimetallic joint is comparable with the samples fabricated using a conventional process. A copper alloy/stainless steel (CuAl-15/SS316)

bimetallic joint processed using explosive bonding has a shear strength ~200 MPa [31]. Fractography of the sheared surfaces showed different modes of failure and failure patterns exhibited by these materials. In Fig. 6a, Inconel 718 exhibited ductile fracture mode which revealed the presence of substantial amount of evenly distributed fine dimples across the sheared surface. Such a failure mode was similar to the fracture pattern reported by Qi et al. [32] and Zhao et al. [33], for tensile testing. On the other hand, GRCop-84 containing approx. 88 wt% Cu exhibited a failure pattern like a brittle material, contrary to the ductile behavior of pure Cu. This was evident on the sheared surface morphology with cleavage and ridges features, including lumps shown in Figure 6b. Although processing techniques influence material's microstructure and mechanical behaviors, the presence of porosities under shear stress could initiate cracks resulting into low shear and compressive strengths exhibited by the copper alloy. The bimetallic joint fractography shown in Fig. 6c portrayed apparently a combined trans-granular and intergranular fracture pattern, indicating a mixed ductile-brittle failure mode. The combined failure mode at the joint was not surprising and could well be predicted due to single-phase solid-solution of Ni-Cu at the interphase. Ni and Cu are the main constituent elements of Inconel 718 and GRCop-84 alloys, respectively, with good metallurgical compatibility. Therefore, the interactive fracture characteristics of the base alloys at the bimetallic interface could well be influenced by such solid solution phase.

Evaluation of compressive yield strengths of tested samples showed a trend similar to shear test, with Inconel 718 having the highest value followed by the bimetallic joints, and the lowest was GRCop-84 again, as shown in Fig. 9. From Inconel 718 ductile deformation behavior, visible failure plane at angle ~50° to the compression axis was clear. Such slip plane phenomenon usually occurs during plastic deformation which was evident on the sample, shown in Fig. 8. A commercially processed GRCop-84 has good ductility [34] compared to the LENS processed with brittle fracture behavior which could be attributed to rapid solidification during processing, resulting into fine grain structures. Heat treatment influences the strength of Inconel 718 and copper-chromium alloys through precipitation strengthening effect. Gamma prime (γ') and gamma double prime (γ'') secondary phases for Inconel 718 [35], while Cr_2Nb particles for GRCop-84 through Hall-Petch mechanism and Orowan strengthening [25]. This was obvious looking at the compressive yield strength including the elastic modulus of the bimetallic joints which increased by ~43% after thermal cycling, as shown in Fig 10. However, at these compressive yield loads, the bimetallic interfacial joints showed no sign of crack initiation/propagation along or through the interface, as observed in the backscatter electron images shown in Fig. 11b and c, even at higher magnifications. This suggests improved interfacial joint strength and mechanical reliability of the bimetallic joint. The stability of the joint region after thermal cycling could be attributed to increased elemental diffusion of Ni and Fe including agglomeration of Cr-Nb particles along the interface, as observed in EDS analysis in Fig. 12 and correlated with higher intensity of white deposits seen in Fig. 11c.

In the low magnification images in Fig 11b and c, a region about 200 μm above the bimetallic joints' interface appears to arrest cracks propagating from the bulk of GRCop-84. The "crack arrest" region inhibits severe deformation and appear to prevented cracks from reaching the interface. The reason for the formation of such region is still not well

understood but is most likely due to improved ductile behavior of the initial copper alloy layer deposited on Inconel 718. This layer experiences slow solidification rate owing to low thermal conductivity of Inconel 718, unlike at the bulk of GRCo-84 where solidification rate was rapid due to high thermal conductivity of the copper alloy. Another explanation for this phenomenon could be the upward diffusion of Ni and Fe element.

In general, both compressive yield and shear strength results of the bimetallic joints showed an increase in bond-strength about 43% and 100%, respectively for as-printed condition compared to the base material, GRCo-84. Such improved bond strength suggests good metallurgical bonding at the interface. Meanwhile, after thermal cycling, the high increase in compressive yield strength compared to shear strength, ~ 45% and 5%, respectively, was attributed to increase brittle characteristics of GRCo-84 due to dispersion strengthening of Cr₂Nb particles. Such effect has less influence during shear testing since deformation was mainly on a small section, the interfacial zone. However, in compression testing, the bulk of structure was under deformation, including the embrittled copper alloy section, which leads to high increase in the compressive yield strength compared to shear strength.

5. Conclusions

A novel single-shear test device was developed to evaluate the interfacial strength of additively manufactured bimetallic joint. The shear and compression strengths of Inconel 718/GRCo-84 bimetallic-joint and base-materials were tested. Both shear strength and compressive yield strength of the bimetallic joints were higher compared to GRCo-84. No evidence of cracking was observed through or along the interface of the bimetallic joint, even after thermal cycling. This suggests good interfacial joint strength and mechanical reliability of the bimetallic joint. Meanwhile, with improved joint strength after thermal cycling, it indicates no thermal degradation on the bimetallic interfacial joint. The increase in yield strength after thermal cycling could be attributed to gamma strengthening phases in Inconel 718 matrix, plus precipitation of Cr₂Nb particles in GRCo-84. The bimetallic joint fractography showed a mixed mode of fracture, indicating a combined ductile-brittle failure mode attributed to a single-phase solid solution of the parent alloys. The single-shear test device could help to analyze reliability and reproducibility of additively manufactured multi-material structures for various room and high temperature applications.

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Fig. 1.
The single-shear test device. (a) As-fabricated. (b) Schematic.

Fig. 2. Single sheared surfaces: (a) Commercial materials and shear strength values compared to published data, (b) LENS processed samples

Fig. 3.
 Single shear model (a) pure material, (b) bimetallic joint, (c) bimetallic shear-zone

Fig. 4.

Shear stress vs. displacement curves for LENS processed Inco 718, GRCop-84 and bimetallic joint. [(A) = as-printed, (T) = after thermal cycling]

Fig. 5. Shear strength of LENS processed Inconel 718, GRCop_84 and Bimetallic joint. [(A) = as-printed, (T) = after thermal cycling].

Fig. 6.
SEM images of sheared surfaces. (a) Inconel 718 (b) GRCo-84 and (c) Bimetallic joint

Fig. 7.
SEM images of sheared bimetallic interfacial-joint. (a) as-printed, (b) after thermal cycling

Fig. 8.
LENS processed samples before and after compression test.

Fig. 9. Compressive stress vs. strain curves for LENS processed Inconel 718, GRCop-84 and bimetallic joint [(A) = as-printed, (T) = after thermal cycling].

Fig. 10. Compressive Yield Strength and Elastic Modulus of LENS processed Inconel 718, GRCop_84 and Bimetallic joint.

Fig. 11.

Backscattered electron images of the bimetallic joint cross-section: (a) as-printed before compression test, (b) compression test on as-printed and (c) compression test after thermal cycling. [ED-AP = elemental diffusion of Ni, Fe and agglomeration of Cr-Nb particles].

Fig. 12.

EDS dot map of the bimetallic joint cross-section showing upwards diffusion of Ni and Fe elements including agglomeration of Cr-Nb particles at the interface.

Table 1.

LENS process parameters for Inconel 718/GRCop-84 bimetallic structure

	Laser Power (W)	Laser scan speed (m/min)	Hatch distance (μm)	Layer thickness (μm)
Inconel 718	450	0.5	530	250
GRCop-84	450	0.4	530	100

Powder feed rate ~12 g/min

Table 2.

Mechanical properties results.

	Shear Strength (MPa)	0.2% Compressive Yield Strength (MPa)	Elastic Modulus (GPa)
Inconel 718	653 ± 11	712 ± 38	41 ± 4
GRCop-84	110 ± 5	162 ± 11	11 ± 0.3
Bimetallic joint (A)	220 ± 18	232 ± 3	17 ± 0.6
Bimetallic joint (T)	231 ± 27	337 ± 15	23 ± 1

(A) = As-printed (T) = after Thermal cycling Number of samples, n = 3