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Characterizing Interfacial Bonds in Hybrid Metal AM Structures

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Abstract

The capabilities of various metal Additive Manufacturing (AM) processes, such as Powder Bed Fusion - Laser (PBF-L) are increasing such that it is becoming ever more common to use them in industrial applications. The ability to print atop a substrate broadens that scope of applications. There is ongoing research regarding the mechanical properties of additively processed materials, but not much regarding the interaction between additive material and its substrate. An understanding of the mechanical and performance properties of the AM/substrate interface is imperative. This paper describes a study of the strength properties of AM/substrate interfaces, with respect to torsion and tension, and compares them to their fully wrought and fully additive counterparts.

Introduction

There is an overwhelming amount of waste in the metal tooling industry. It is generally not worth the time or money to repair a metal tool, as it is cheaper to simply replace it. This is especially true when the tool needing replaced is either very simple, thus being easy to mass produce, or very intricate, making it difficult to repair. There are various methods used to repair metal products. Metal filled epoxies, mechanical fasteners, and welding techniques are common solutions to reworking parts for continued use. Reworked tools and products tend to have decreased mechanical properties that may influence their performance. In many industries the safety standards require mechanical properties that are unattainable through these common reworking processes. A remanufacturing process that provides similar or better mechanical properties than the original part, while also being time and cost effective, is a current need in the engineering and manufacturing fields.

Additive manufacturing (AM) is one viable solution to this need. The last decade has seen an explosion of growth in metal additive manufacturing processes [1]. The quality and consistency of these processes [2] are reaching sufficient levels to support not only rough prototyping, but repair, tool design, and even full-scale manufacturing. There are numerous benefits to producing metal parts additively, rather than by other conventional casting and machining methods. Time, money, and resources can be preserved, while also dramatically increasing design flexibility [3]. Custom parts can be fabricated rapidly, from design phase to solid part, in a matter of hours. This research focuses on the remanufacturing capabilities of AM.

Utilizing AM as a remanufacturing process, many tools and products could be repaired rather than replaced, saving both time and money [4]. New material and features can be printed directly onto existing parts and structures, allowing the flexibility of AM without the relatively high cost of printing a new part from scratch. However, the mechanical properties of the additively manufactured features and their interface to the substrate material must be sufficient to meet or exceed the requirements of the original part in order for this process to be viable.

This paper describes the material properties testing of samples produced by printing stainless steel material onto a substrate of the same material, with a focus on the properties at and near the interface. There has been very little research focusing on the interfacial bond between a metal AM part and a substrate, although it has been touched on [5]. Validating metal AM as a reliable process for repair of metal tools will have massive implications on many industries worldwide.

Methodology

In order to gain a better understanding of the mechanical properties and capabilities of the interface between AM material and a substrates, samples of SS316L stainless steel were prepared for torsion and tensile testing. Torsion and tensile tests were performed on three different categories: fully wrought specimens, fully additive specimens, and hybrid (AM/substrate) specimens. Both torsion and tensile specimen designs are according to ASTM E8 specifications. The methods for testing these pieces allowed for both torsion and tensile tests to be run on the same Instron machine by simply altering the test method and switching the jaws.

Sample Fabrication:

The specimens were prepared from three blocks of material (Figure 1):

One block wrought SS316L (0.5" x 2.25" x 3.0")

One block AM SS316L (0.5" x 2.25" x 3.0")

One hybrid block consisting of a 0.5" x 2.25" x 1.5" block wrought SS316L with additional SS316L of the same dimension printed on top (resulting in a block the same dimension as the other two blocks)

The AM portions of the test specimens were deposited using a ConceptLaser PBF-L type machine, using SS316L stainless steel and a laser power of 49 J/mm^3.

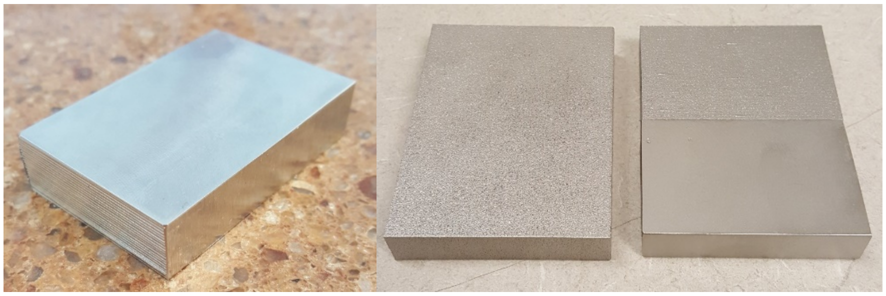

Figure 1. Wrought, AM, and hybrid blocks of SS316L stainless steel

From these blocks, the dimensions in Figures 2 and 3 were used to prepare the following specimens (Figure 4):

3 torsion test specimens of wrought SS316L

3 torsion test specimens of AM SS316L

3 torsion test specimens of hybrid AM/wrought SS316L

3 tension test specimens of wrought SS316L

3 tension test specimens of AM SS316L

3 tension test specimens of hybrid AM/wrought SS316L

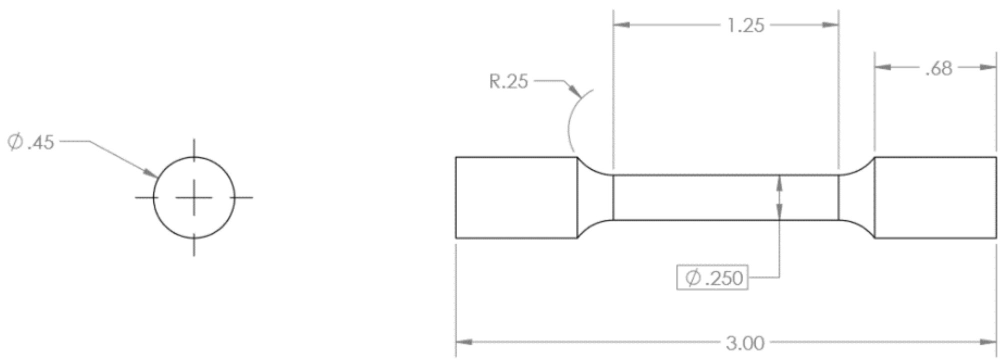

Figure 2. Torsion test specimen (all dimensions in inches)

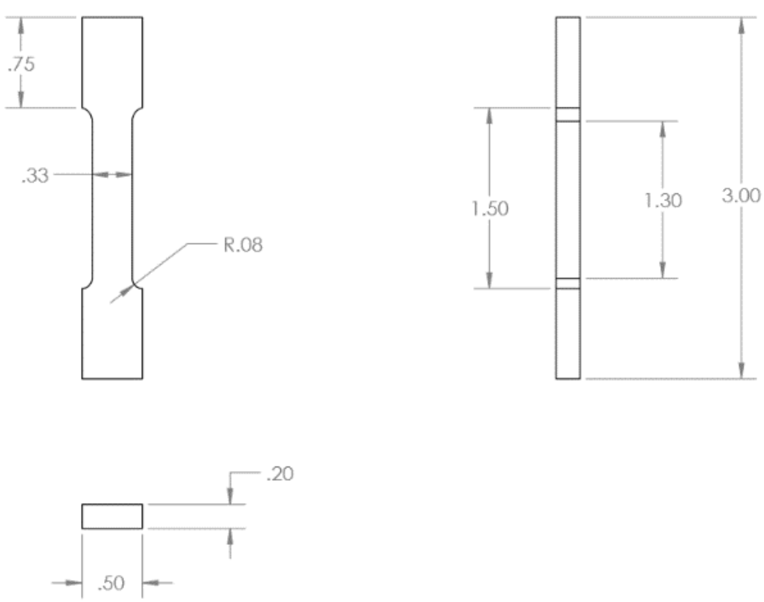

Figure 3. Tension test specimen (all dimensions in inches)

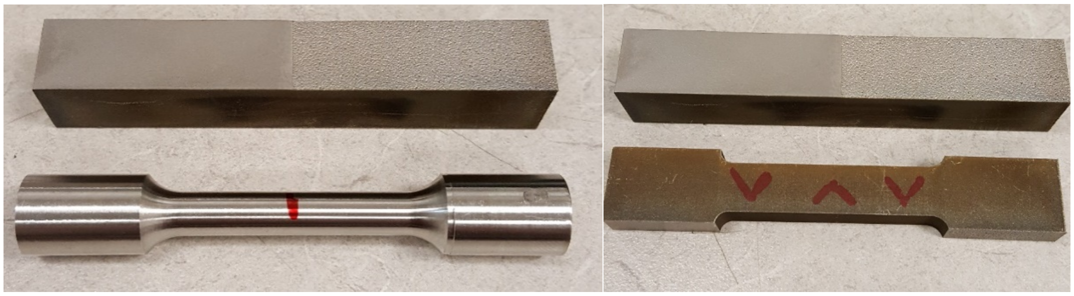

Figure 4. Torsion and tensile test specimens of hybrid AM/wrought SS316L

Torsion Testing:

Each torsion test specimen was placed in an Instron Tensile Tester machine (Figure 5) with a 10,000 lb-in torque load capacity. The first sample was loaded in torsion through 45 degrees of rotation. All subsequent samples were submitted to 90 degrees of motion (registered in the data as from -45 to +45 degrees). Wave Matrix software was used to perform the experiments consistently and gather pertinent data (torque load vs. degrees twisted) to aid in making observations and drawing conclusions. Pictures were taken of the test specimens before and after testing in order to more accurately conclude what occurred.

Tensile Testing:

Each tensile test specimen was placed in an Instron Tensile Tester machine with a 20,000 lb. tensile load capacity. The samples were loaded in quasi-static tension until ultimate failure. Wave Matrix software was used to perform the experiments consistently and gather pertinent data (tensile load vs. elongation torque load vs. time) to aid in making observations and drawing conclusions. Pictures were taken of the test specimens before and after testing in order to more accurately conclude what occurred.

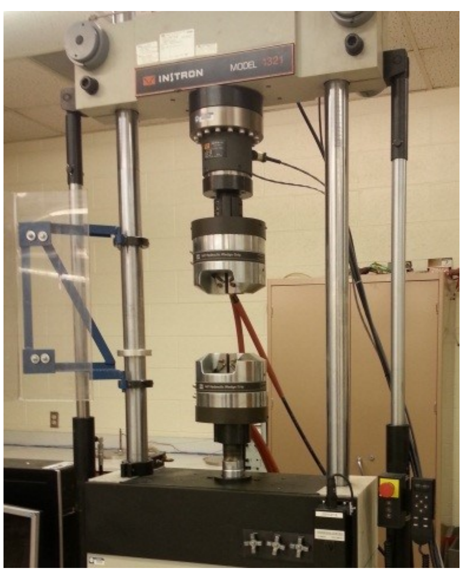

Figure 5. Instron machine used for torsion/tensile testing

Results

Torsion Testing:

The first specimen tested, Wrought SS 1, was subjected to 45 degrees of rotation, the limit of the Instron machine when starting from zero degrees. As shown in Figure 6, the material yielded, but continued to plastically deform without full failure. Because of this, the second specimen, Wrought SS 2, was subjected to 90 degrees of rotation, from -45 to +45 degrees on the machine, with similar results. The third wrought specimen was tested repeatedly by twisting the sample through 90 degrees, refixturing it in the machine, and twisting it again. After multiple full rotations, the specimen continued to plastically deform without failure. Data from Wrought SS 3 is not included below, due to the deviation from the test procedure. All subsequent specimens were subjected to 90 degrees of rotation like Wrought SS 2. Results of these tests are shown in Figures 6-8.

Tensile Testing:

All nine tensile test specimens were tested until failure according to the test procedure in the previous section. Results of these tests are shown in Figures 9-11.

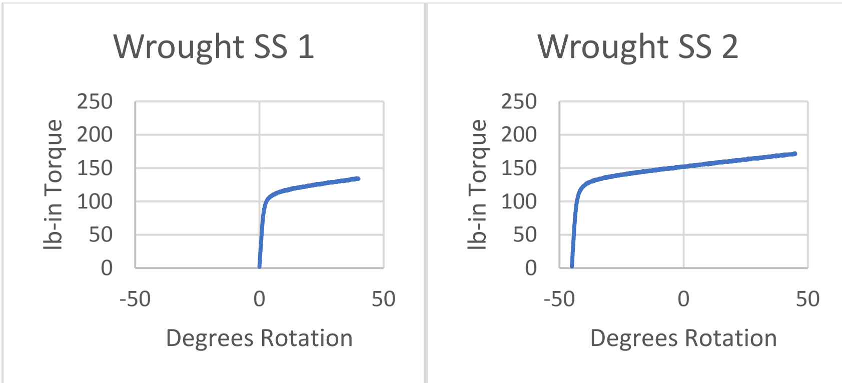

Figure 6. Torque vs. rotation for wrought torsion specimens

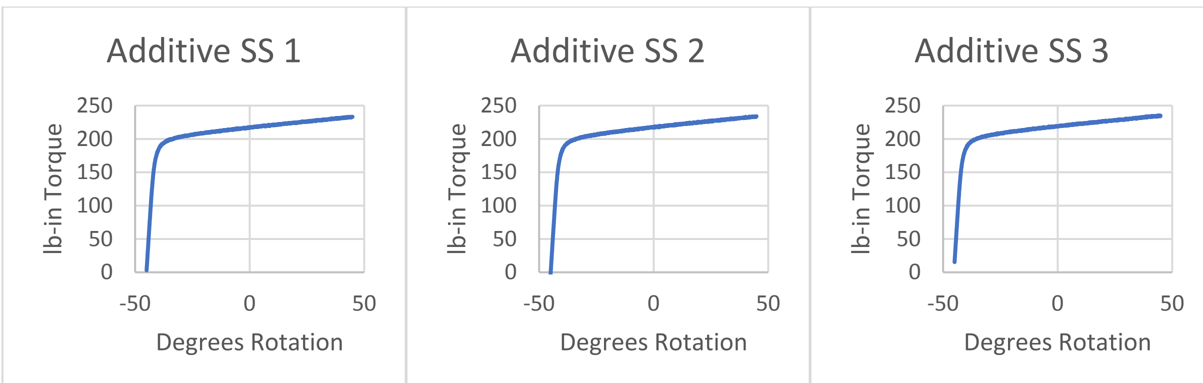

Figure 7. Torque vs. rotation for AM torsion specimens

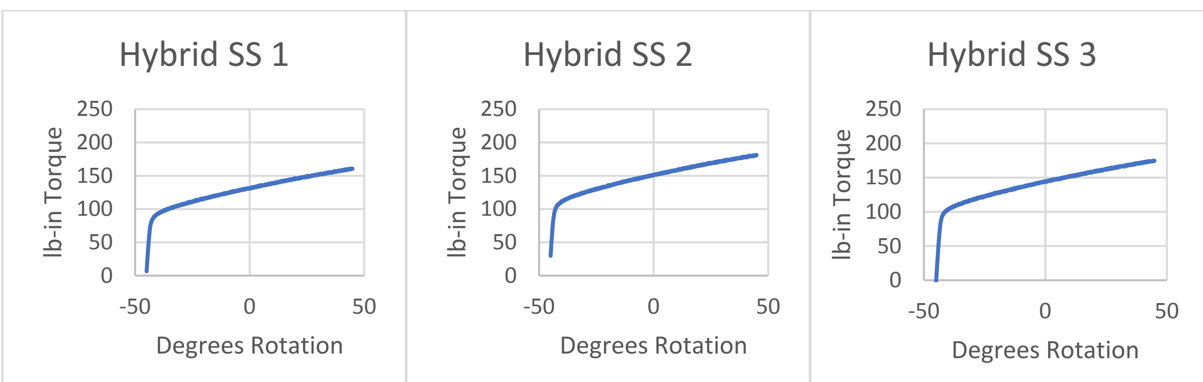

Figure 8. Torque vs. rotation for hybrid torsion specimens

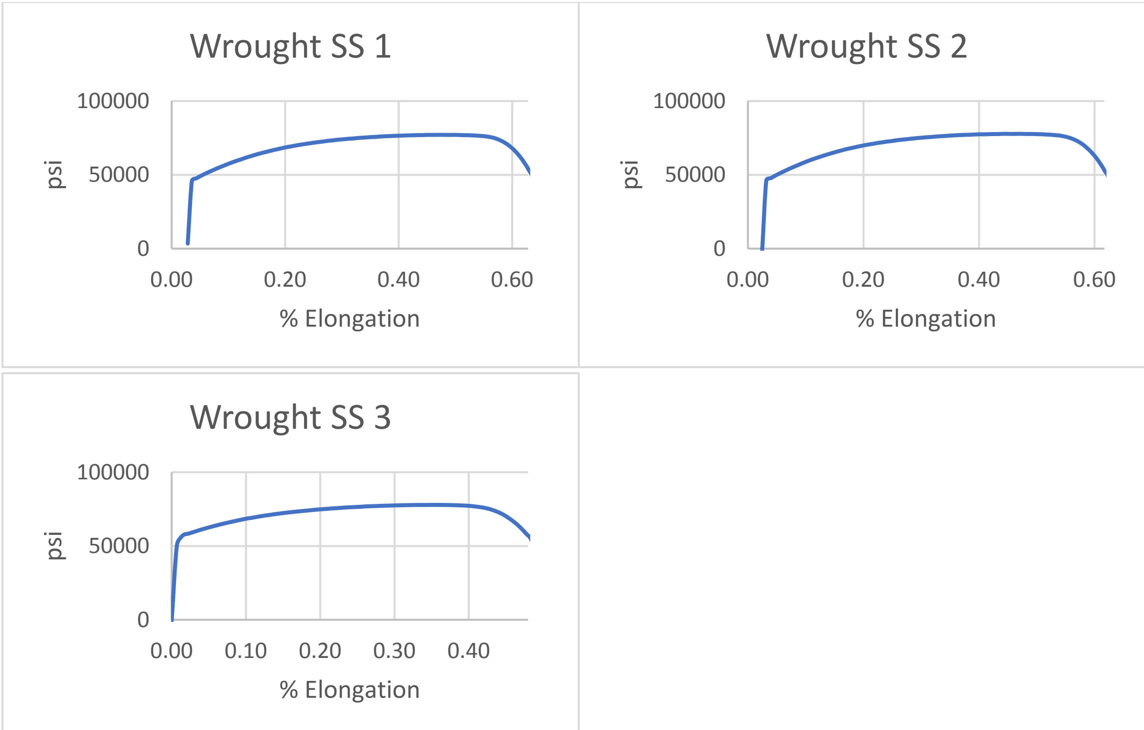

Figure 9. Tensile stress vs. % elongation for wrought tensile specimens

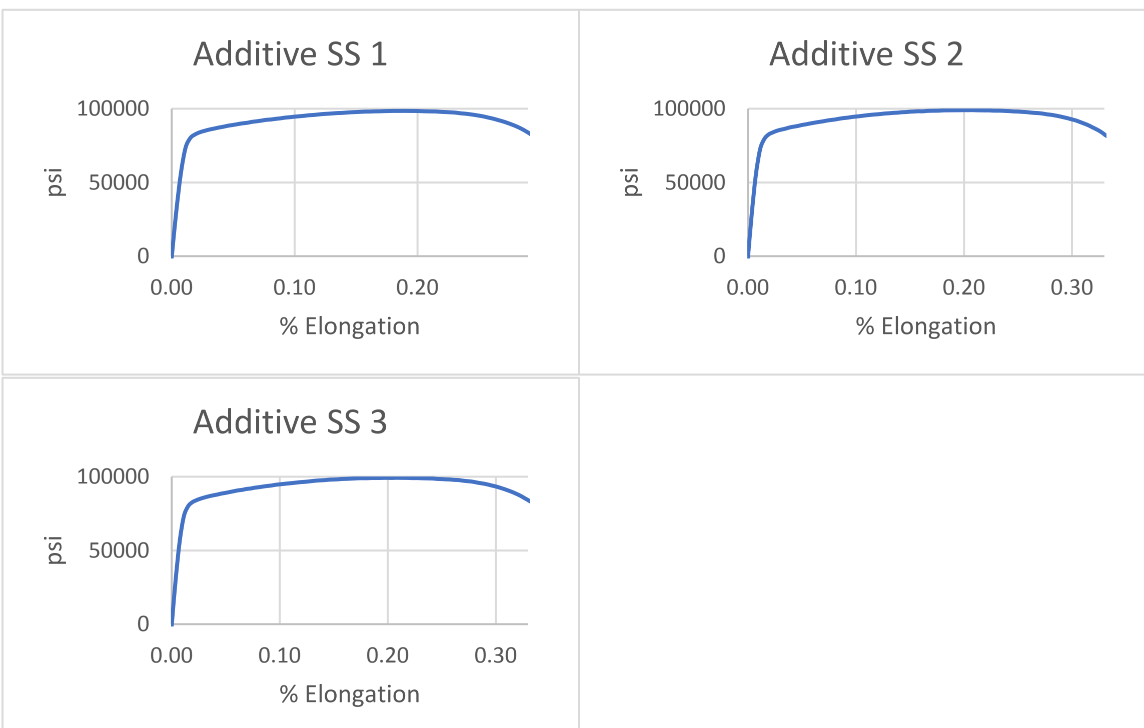

Figure 10. Tensile stress vs. % elongation for AM tensile specimens

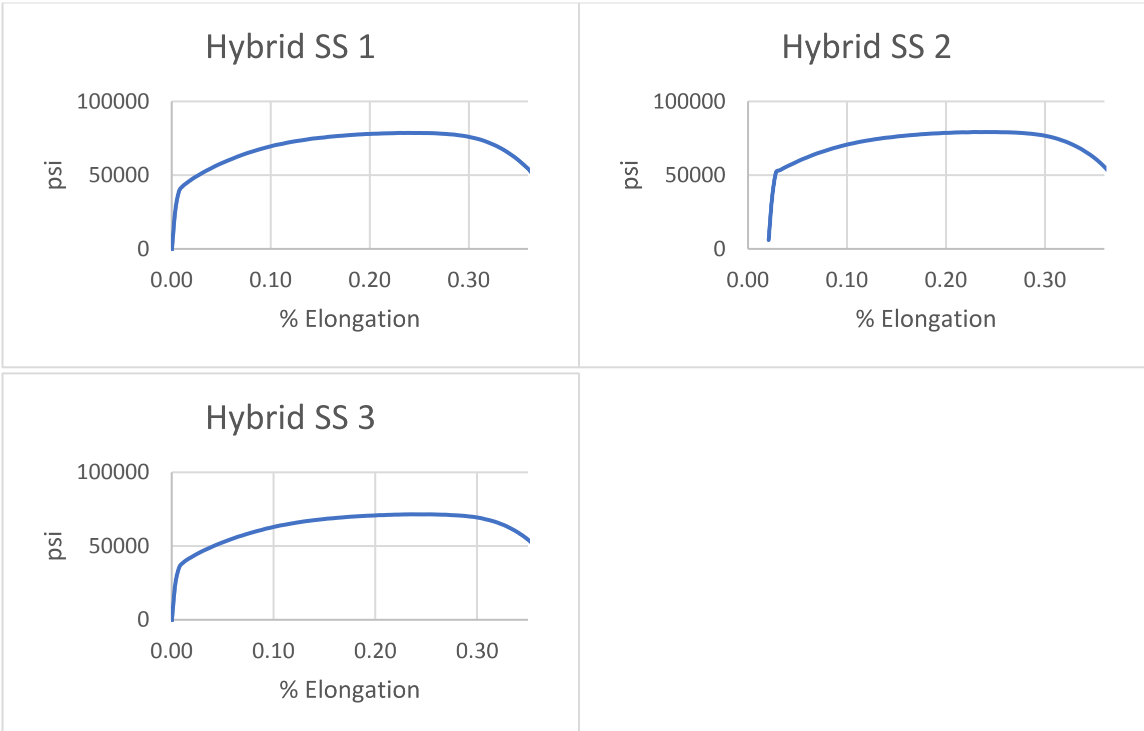

Figure 11. Tensile stress vs. % elongation for hybrid tensile specimens

Discussion

Torsion Testing:

As shown in Table 1, the wrought test specimens exhibited an average torsional yield strength of 36,000 psi (248 MPa). The AM test specimens exhibited significantly higher strength in torsion, with an average of 65,000 psi (448 MPa). The hybrid test specimens yielded in torsion at an average of 30,000 psi (206 MPa), similar to the wrought specimens. Visual inspection confirmed that all three hybrid specimens yielded primarily within the wrought material, with no visible deformation within the AM portion of the specimens (Figure 12). All other specimens, both wrought and fully AM, yielded near the midpoint of the neck.

Table 1. Average torsion and tensile strengths of test specimens

	Wrought SS316L	PBF-AM SS316L	Interface SS316L
τ_{yield}	36,000 psi (248 MPa)	65,000 psi (448 MPa)	> 30,000 psi (> 206 MPa)
σ_{yield}	45,000 psi (310 MPa)	80,000 psi (552 MPa)	> 40,000 psi (> 276 MPa)
$\sigma_{ultimate}$	78,000 psi (538 MPa)	99,000 psi (683 MPa)	> 75,000 psi (> 517 MPa)

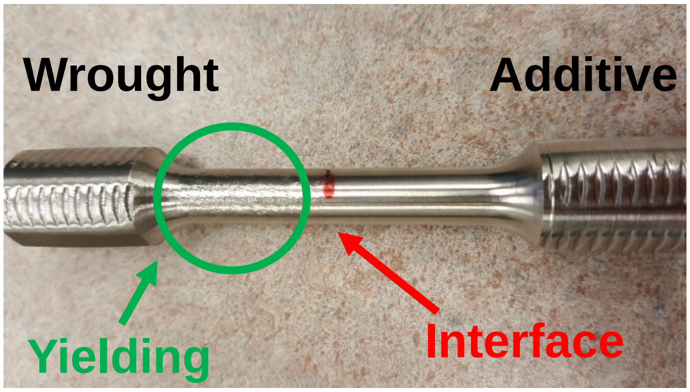

Figure 12. Hybrid torsion specimen showing yielding

Tensile Testing:

Table 1 also shows the average tensile yield and ultimate strength for each set of specimens. As with the torsion tests, the AM specimens exhibited significantly higher strength than the wrought specimens. The hybrid specimens exhibited average yield strength of 40,000 psi (276 MPa) and ultimate strength of 75,000 psi (517 MPa), which is similar to the strength shown by the wrought samples. Again as with the torsion tests, visual inspection confirmed that the hybrid specimens all failed within the wrought material, well away from the interface between AM and wrought (Figure 13). All other specimens, both wrought and fully AM, yielded near the midpoint of the neck.

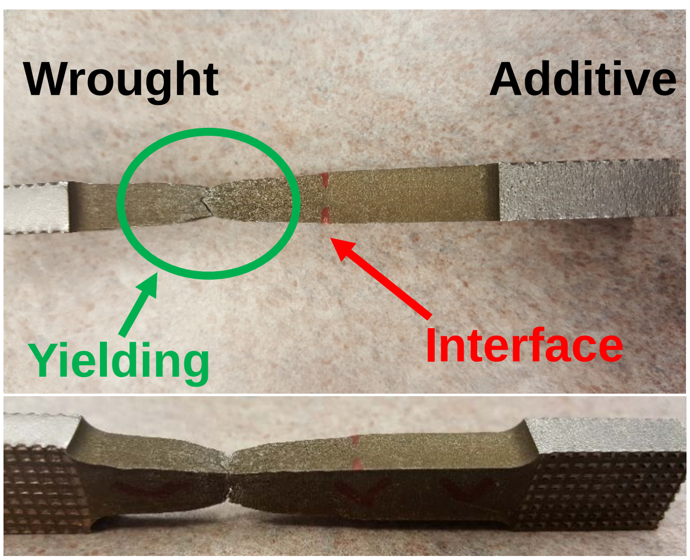

Figure 13. Hybrid tensile specimen showing yielding and fracture

Predicted Strengths at the AM/Wrought Interface:

Because all hybrid specimens yielded within the wrought material, not at the interface with the AM material, material properties of the interfacial bond could not be directly measured. However, as there appeared to be little to no yielding in this region of the specimens, we can put a lower bound of the interfacial strength at the failure of the wrought material. Thus in Table 1, the torsional and tensile yield strengths listed can be considered minim strengths, with the actual strengths at the interfaces considerably higher. It is unknown from these experiments whether the interfacial strength would be similar to the strength of the AM material or whether it would be somewhere between the two extremes.

Conclusion

From these eighteen tests, there are a few valuable conclusions that can be made:

First, the AM specimens of SS316L stainless steel all had much higher yield and ultimate strengths than the wrought specimens. There are significant processing differences between wrought metal and the micro-welding of laser-powered powder bed fusion [6]. It is expected that such differences will lead to differences in the two materials' microstructure as well. We hypothesize that the micro-welding process of PBF results in smaller and more uniform grain boundaries than the working process. Future work for this study includes microscopic analysis of the grain structure of the two materials and the interface region between them.

A second conclusion is that the interfacial bond of SS316L AM/substrate specimens outperforms the original wrought material in both torsion and tension when using PBF-L as the additive process. The actual bond strength limits in torsion and tension were never reached. This is an encouraging result for applications such as repair and rework of rotary tools, molds, and other work pieces, as the newly deposited material and its bond to the wrought material appears to be predictably stronger in tension and torsion than the original part. Further characterization of the AM material and the interfacial bond in terms of impact hardness, ductility, bending, T-peel, etc. may be beneficial in fully understanding the tradeoffs in this area.

Additional future work planned for this research area include performing this study using a different AM process (direct energy deposition), performing the study using PBF-L and one or more different alloys (such as M300 steel), and the previously mentioned analysis of grain microstructure before and after each of these tests.

Works Cited

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