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TECHNICAL ARTICLE

Comparison of Stress–Strain Properties from Profilometry-Based Indentation Plastometry (PIP) and Conventional Tensile Testing

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Profilometry-based indentation plastometry (PIP) was studied in this research to obtain stress–strain data from a simple indentation test. Five alloys commonly produced by additive manufacturing, Ti6Al4V, Ahead CP1, AlSi10Mg, Ni625, and Ni718, were used to print tensile bars using laser powder bed fusion (L-PBF). The tensile bars were then tested using the 'gold standard' of mechanical testing, conventional tensile methods outlined in ASTM E8. The tested tensile specimens were then sectioned through the grip section and polished using standard metallographic preparation techniques and PIP tested. When comparing the two test methods, the average tensile strength between all the materials showed a difference of 3.2% while the yield strength differed by 3.7%. These small differences between testing methods demonstrate that PIP testing is a viable alternative to the tensile test. Particular attention was given to the variation in the PIP-determined properties, and the origins of this variation are discussed. A test method standard is currently being developed for this methodology through the ASTM F42 committee, and therefore independent data to assess the precision and accuracy of the method are required.

INTRODUCTION

Additive manufacturing (AM) is a manufacturing technique that has grown significantly in popularity in the past decade especially within the aerospace, automotive, and medical fields. AM can produce parts with complex geometries with quick turnaround and decreased material waste. Within AM, laser powder bed fusion (LPBF) has become a prominent technique due to its finer surface finish, better dimensional accuracy, and higher output due to the minimal postprocessing compared to other AM methods, such as directed energy deposition and electron beam melting. LBPF works by layering metallic powder on a "bed" and using a CAD model to direct a high energy laser to selectively melt the powder layer by layer.

While AM has developed into a widely used production technique, the need for rapid testing has grown to verify a printed part's mechanical properties. One of the most common and reliable used tests for evaluating a material's properties has been the tensile test, which applies a uniaxial stress on a coupon of set dimensions to determine the stress–strain curve of the material. The information gathered in this test provides valuable insight into a material's, and thus part's, performance capability. The test itself is relatively quick, but the equipment needed for testing, time for set-up, and machining of the coupons limits the practicality and turnaround time.

The PLX-Benchtop is a new piece of testing equipment from Plastometrix to help solve these issues. The PLX-Benchtop uses profilometry-based indentation plastometry (PIP) testing,[1] a method to determine a material's stress–strain curve from an indentation. The method involves three key steps:

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1. Creation of an indent 100–200 μm deep using a spherical indenter.
2. Measurement of the residual indent profile using an integrated stylus profilometer.
3. Analysis of the residual indent profile using inverse finite element method analysis (FEM).

This method is automated on the PLX-Benchtop using its dedicated testing software, CORSICA. There are several advantages of PIP testing compared to standard tensile testing. These include the small volume of material required for a test (as small as 3 mm $\times$ 3 mm $\times$ 1.5 mm) and simple sample preparation requiring a P1200-grit surface finish and two parallel flat sides. Compared to the volume of material and preparation required for an ASTM E8 tensile bar, these can lead to significant material, time, and cost savings. Additionally, as an indentation-based technique, material properties can be mapped as a function of position across a build volume.

Data comparing PIP with tensile test results is available for extruded products,[2] sprayed superalloy coatings,[3] a new superalloy produced by LPBF,[4] welded components,[5] stainless steel produced by binder jet,[6] maraging steel produced by LPBF,[7] friction stir welded components[8] and metal matrix composites.[9,10] For this method to be widely adopted in the AM space, there is a need for more comprehensive data comparing PIP testing results with those from convention tensile testing. Therefore, this work compares PIP test data on five common AM alloys process by LPBF: Ti-6Al-4V, CP1, AlSi10Mg, Ni625, and Ni718.

While there are several advantages to PIP testing, users must also be aware of the limitations. As an indentation-based testing technique, while it stimulates plastic deformation in the metal, there is typically no fracture type phenomena that occur during the test. Therefore, this technique cannot be used to measure the elongation at break or reduction of area that would be measured during a tensile test. There are also limitations on the grain size of the material, with the maximum allowable grain size approximately one-half of the indenter radius. Therefore, when using a 1-mm-radius indenter, the maximum allowable grain size is approximately 0.5 mm. Finally, as PIP uses the Voce law,[1] an empirical equation widely used to model plasticity with three parameters (a yield stress, saturation stress, and characteristic strain), it cannot capture features such as discontinuous yielding that can take place during tensile testing, e.g., Luders band formation in low carbon steels (Fig. 1).

Fig 1. The PLX-Benchtop and its components.

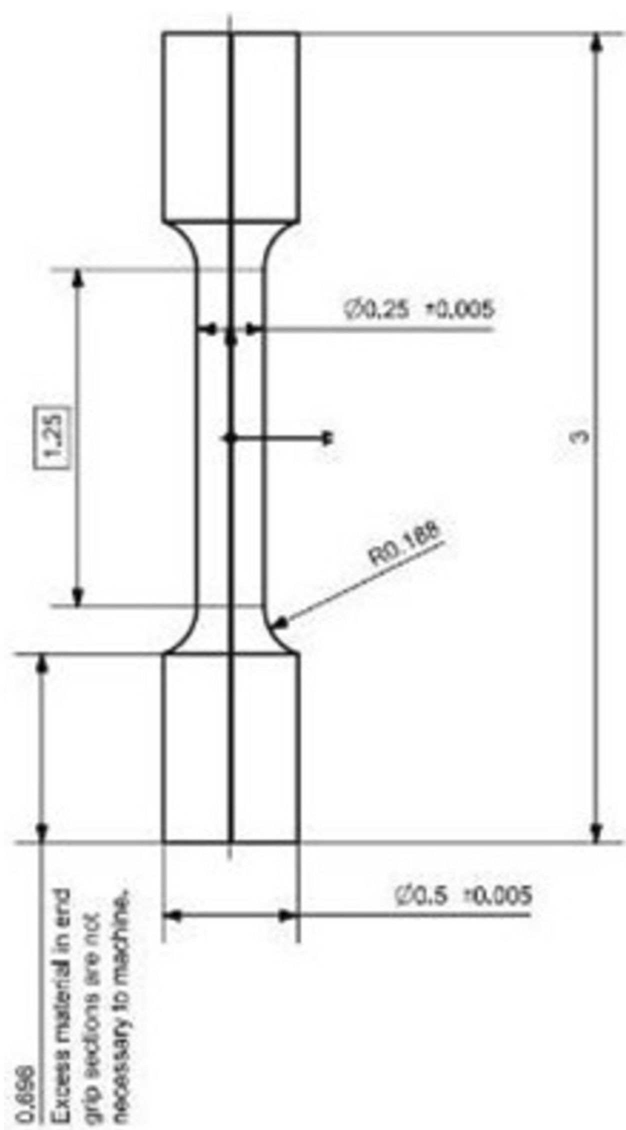

Fig 2. ASTM standard E8 subsize coupon 4D, specimen 3.

EXPERIMENTAL

Ten tensile coupons manufactured in the vertical direction conforming to Fig. 2 of Ti6Al4V, CP1, AlSi10Mg, Ni625, and Ni718 were printed using LBPF on an EOS M400 and heat-treated (see Table I). The ten samples of each material were then tested using the standard tensile testing method outlined in ASTM E8.

Table I. Heat treatments used on the five different alloys for testing

Material	Heat Treatment	Printer
Ti 6-4	1475°F (802°C) for 2 h	M400-4
AlSi10Mg	550°F (288°C) for 1 h	M400-1
Ni625	1400°F (760°C) for 1 h	M400-4
Ni718	ST: 1750°F (954°C) for 1 h (air-cooled) Age: 1325°F (718°C) for 8 h 1150°F (621°C) for 10 h	M400-4
CP1	725°F (385°C) for 4 h	M400-4

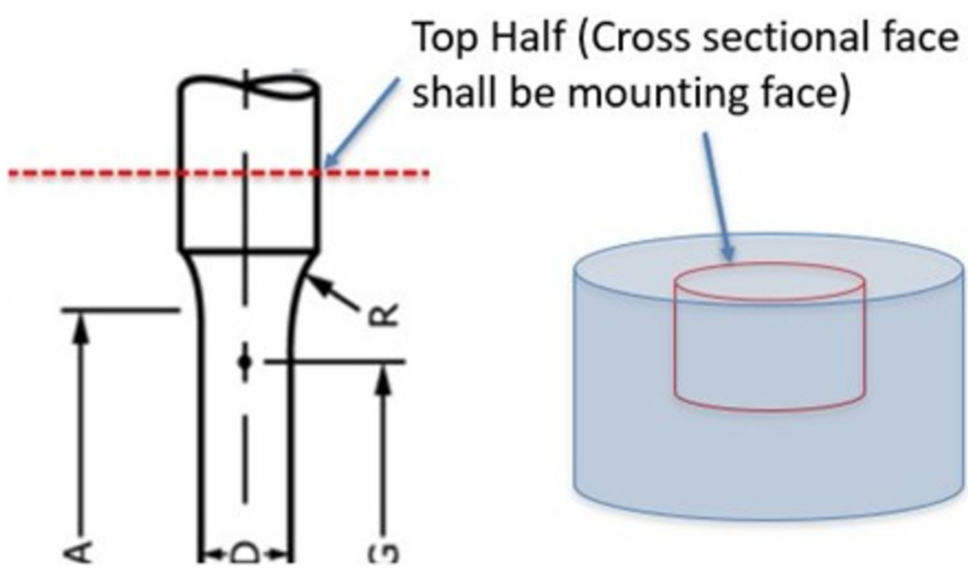

Fig 3. Sectioning method used on tested tensile samples.

Each of the tested tensile samples were then sectioned in the grip of the coupon (see Fig. 3). Ten sections (one from the end of each tensile bar) were produced in total for each material. All these specimens were mounted in the *XY*-plane, such that the indentation was carried out along the build direction to ensure that a radially symmetric indent was produced.[4] Once mounted, the samples were ground and polished to a mirror finish using standard metallographic preparation techniques. The samples were then tested using the PLX-Benchtop with a 1-mm-radius indenter tip made from silicon nitride. Three tests were carried out on each coupon, for a total of 30 tests per material. Each indent was at least 5 mm from the nearest one.

When setting up testing for each alloy, a material type was chosen within CORSICA. Each material type (aluminum, titanium, nickel, steel, etc.) changes the elastic mechanical properties that are used in the FEM simulations for each test. For the steel and nickel samples, 200 GPa was used for the Young's modulus, while for aluminum and titanium the values were 69 GPa and 115 Gpa, respectively.

RESULTS AND DISCUSSION

Ultimate Tensile Stress Comparison

The results from the ASTM E8 tensile testing and PIP testing are shown in Tables II and III. A total of 30 PIP tests were averaged and 10 tensile tests per material were averaged. The percentage difference between each material was then calculated by taking the difference between the average PIP test and the average tensile test and dividing by the same average tensile value.

In Table II, which compares the ultimate tensile strength (UTS) values, the average percentage difference between PIP and ASTM E8 was 3.2%. The aluminum alloys, AlSi10Mg and CP1, had the lowest difference between values while Ni 718 and Ti 6-4 had the highest. Figure 4 shows this data visualized as bar charts, demonstrating that the PIP closely matches the values measured from the tensile testing. It is possible to observe a correlation between the overall tensile strength of the sample and the difference between the PIP and UTS values, where higher UTS material led to a greater difference, although this is only for a set of five samples.

Table II. Average results from tensile testing and PIP

Material	ASTM E8 UTS (ksi)	ASTM E8 SD	PIP UTS (ksi)	PIP SD	% Difference
Ti 6-4	158	0.87	165.3	3.23	4.4
AlSi10Mg	42.6	1.34	43.1	1.67	1.2
CP1	47.6	0.31	46.6	1.28	2.1
Ni 625	154	3.27	158.2	4.08	2.7
Ni 718	203.6	6.32	215.2	5.62	5.7
UTS % difference average					3.2%

Table III. Summary of yield strength results from PIP and tensile testing

Material	ASTM E8 yield (ksi)	ASTM E8 SD	PIP yield (ksi)	PIP SD	% Difference
Ti 6-4	152	0.72	140.9	3.33	7.3
AlSi10Mg	24.2	1.22	25.4	2.37	5.0
CP1	45.7	0.28	43.9	2.64	0.4
Ni 625	110.9	0.64	110.5	6.88	3.8
Ni 718	175.3	1.19	182	8.5	1.7
Yield % difference average					3.7%

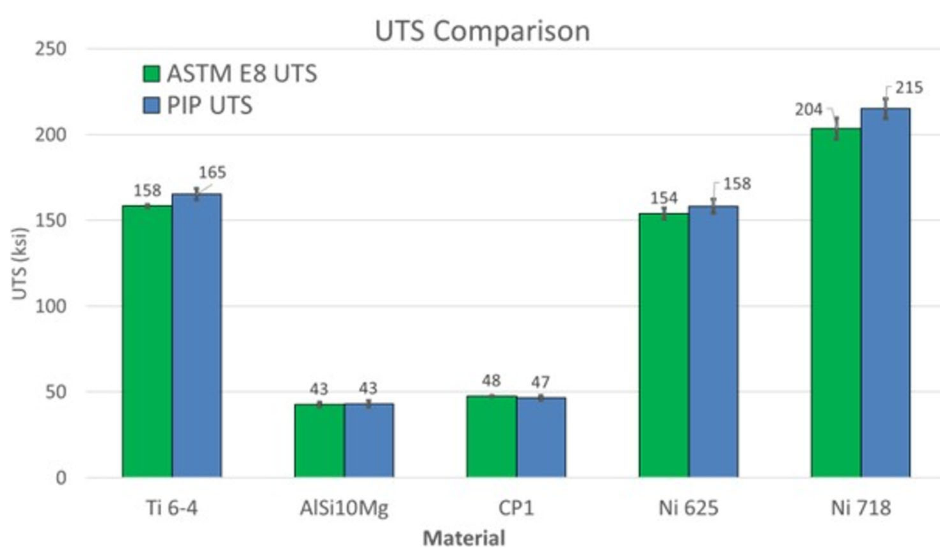

Fig 4. Ultimate tensile strength (*UTS*) results from PIP and ASTM E8 testing.

In Fig. 5, which shows a comparison of the standard deviation of the UTS for each material and test type, in general, PIP has a slightly higher standard deviation in most cases, although the values are comparable.

Yield Stress Comparison

The results in Table III and visualized in Fig. 6 show the comparison of PIP and tensile testing for yield strength. Figure 6 shows that the average value from PIP testing very closely matches the averaged values from the tensile testing. The percentage difference between all five materials was slightly higher, at 3.7%, compared to the UTS difference. The AlSi10Mg, CP1, Ni 625, and Ni 718 all showed a percentage difference of 5% or less between the two different test methods. The yield strength of Ti 6-4 showed the greatest difference between the two test methods at 11 ksi or 7.3% difference. This is likely due to strain rate effects in Ti64 where the strain rate is changed during the tensile test and produces discontinuity in the stress–strain curve.[11] For materials that can be rate-sensitive, this must be kept in mind when directly comparing data from PIP and tensile testing.

In Fig. 7, which shows a comparison of the standard deviation from each test method for the yield stress, in general, the standard deviations from the PIP test are consistently higher than the tensile test. Ni 718 showed the highest standard deviation, at 8.5 ksi, with the yield values.

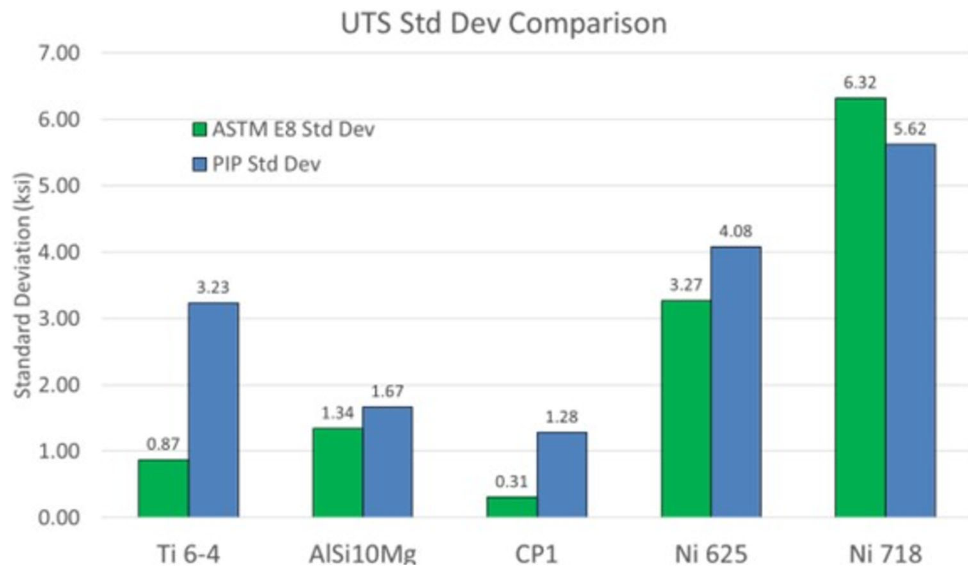

Fig 5. UTS standard deviation comparisons between the two test methods.

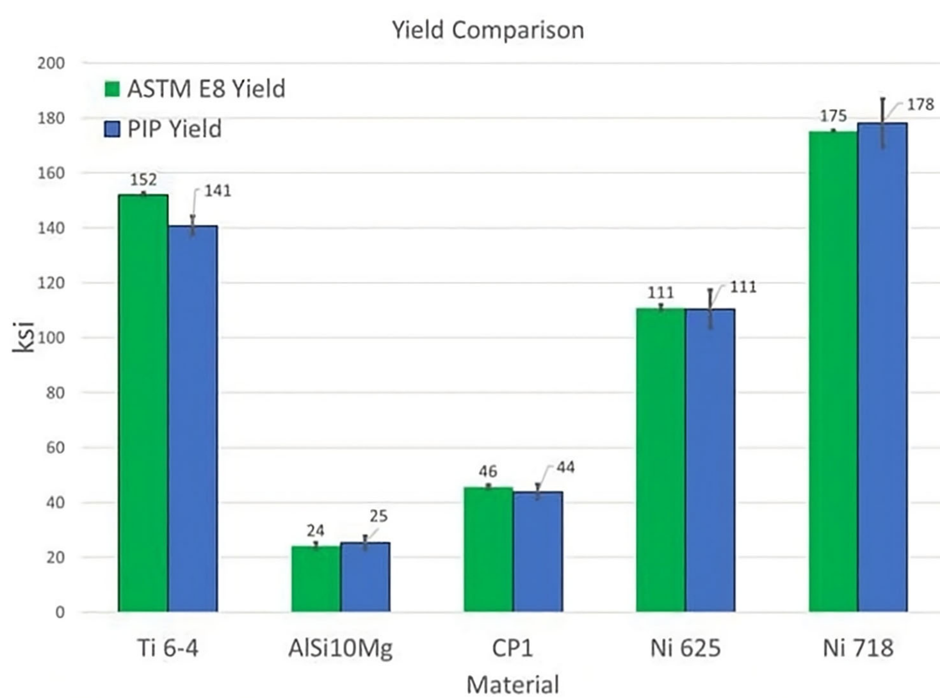

Fig 6. Yield strength of PIP versus uniaxial tensile testing.

Variation During PIP Testing

While the average percentage difference between the different testing techniques is low, and the standard deviation for UTS between the two testing methodologies is similar, the data presented in Fig. 7 demonstrate that the PIP data has a higher standard deviation than tensile testing when evaluating the yield stress. It is important to understand the origins of this variability to see where the method could be further developed.

Figures 8 and 9 examine this in detail for two of the materials in this study, CP1 and Ni718. Figure 8 shows the residual indent profiles from tests on these materials. The depths are comparable, with both indents being close to 200 μm deep, although the loads used to generate these indent depths are significantly different: 6 kN for Ni-718 and 1.5 kN for CP1, reflecting their very different mechanical properties. The pile-up height for Ni-718 is significantly lower than for CP1, which is due to the much higher work-hardening rate that is present in Ni-718, with it acting to reduce pile-up around the

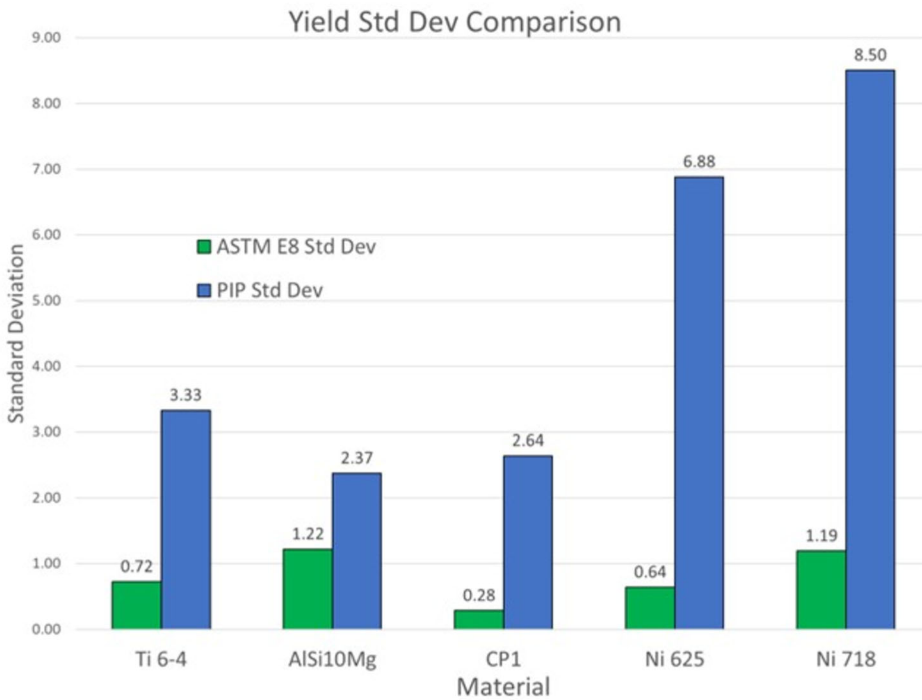

Fig 7. Comparison of standard deviation of PIP versus tensile test.

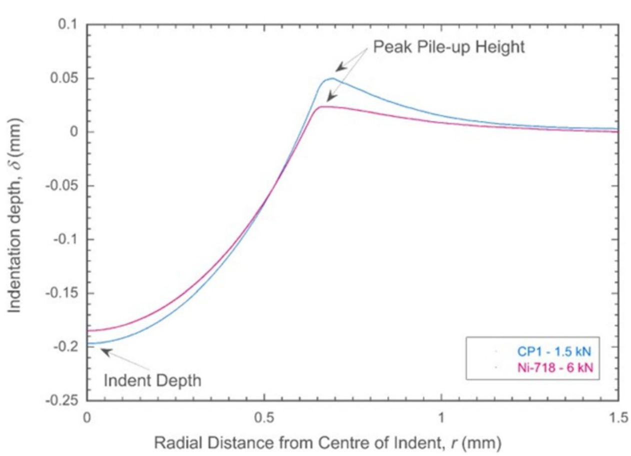

Fig 8. Residual indent profiles highlighting the key features for two materials in this study, CP1 and Ni-718.

indenter. Finally, it is noticeable that the curvatures in these cases are quite different, likely due to the different amounts of elastic recovery taking place during the elastic unloading, which is influenced by a combination of the different elastic moduli of these materials and the stresses under the indenter experienced at maximum load (which is itself a combination of the elastic modulus, applied load, yield stress, and work-hardening behavior).

When using PIP to determine the mechanical properties, the indent depth and peak pile-up height are two key points in the indent profile that will strongly influence the inferred values of yield stress and work-hardening characteristics. An assessment of the variability of these two parameters, as well as the yield stress and UTS determined using PIP, is shown in Fig. 9a and b for Ni-718 and CP1, respectively, with each datapoint for the four variables normalized by the mean value. Note that this can only be done for PIP tests that were all carried out to the same load, so the data shown here are a subset of the 30 tests performed on each material.

Figure 9 shows that the PIP values of UTS show less variation than the PIP values of yield stress. In the profile measurements, for both materials, the indent depths are consistent with the maximum variation within ± 2.5% of the average value. However, the peak pile-up height shows more variation, up to 15% difference from the average in the case of the Ni-718. These variations may appear large, but they must be viewed with the context that the (average) absolute values of the pile up height are 22.2 μm and 50.3 μm for the Ni-718 and CP1, respectively, compared with depth values of almost 200 μm. Nevertheless, these plots suggest that it is the pile-up height variability that is leading to the variation in the PIP which determined yield stress. It could be that this is due to the microstructure of the material and could therefore be countered by using a larger indenter, or it could be that the profile measurement could be improved to reduce the variation. This is an area for further investigation as the methodology matures further.

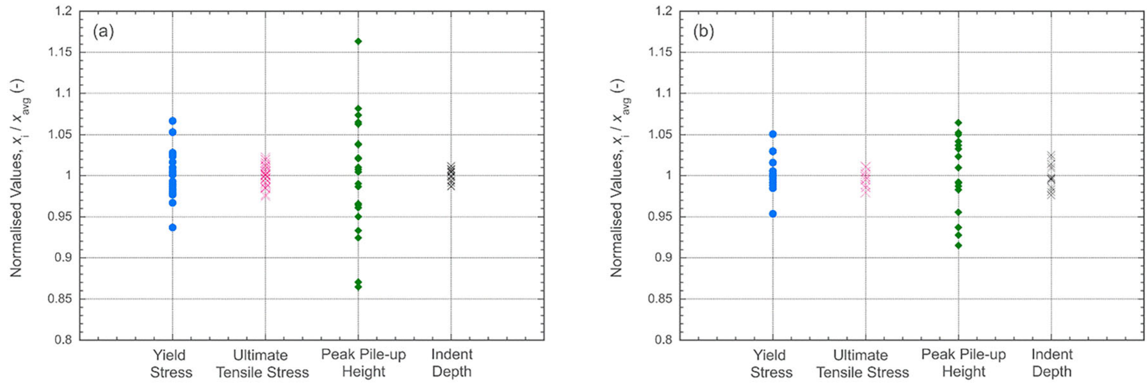

Fig 9. Data for yield stress, ultimate tensile stress, peak pile-up height, and indent depth normalized by the mean value for indents on (a) Ni-718 with a load of 6 kN and (b) CP1 with a load of 1.5 kN.

CONCLUSION

Five different alloys were tested using two different tests methods to gather stress–strain data. The first method was a conventional uniaxial tensile test that follows the ASTM E8 standard, while the other method utilized a PLX -Benchtop that uses an spherical indent and profilometer combined with FEM software to determine the stress–strain curve of the material.

Ten tensile tests were conducted with each material while 30 PIP tests were performed using the PLX-Benchtop. When the averages of both tests were compared, the difference in tensile strength and yield strength differed by 3.2% and 3.7%, respectively. These differences demonstrate the PIP method is a viable option for determining a material's stress–strain properties. The variability in the PIP-determined yield stress was shown to be larger than that in tensile testing, which appears to be due to variation in the measured pile-up height of the residual indent profile.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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