TENSILE PROPERTY ESTIMATES OBTAINED USING A LOW COMPLIANCE SHEAR PUNCH TEST FIXTURE – M. B. Toloczko and R. J. Kurtz (Pacific Northwest National Laboratory)* A. Katsunori and A. Hasegawa (Tohoku University, Japan)

OBJECTIVE

The objective was to further understand the nature of deformation in the shear punch test and to use this information to develop a new shear punch test fixture which would provide a better estimate of tensile properties.

SUMMARY

It has been previously shown that for a wide range of BCC and FCC metals, shear punch properties correlate well with uniaxial tensile properties from corresponding miniature tensile tests. However, recent studies of the shear punch test technique have revealed that by more directly measuring punch tip displacement during a shear punch test, the resulting effective shear stress versus displacement trace has a greater similarity to a corresponding tensile test trace. On the assumption that this would lead to shear punch properties that correlate even better with uniaxial tensile properties, shear punch tests were performed on a variety of unirradiated metals, and the shear punch properties were compared to tensile properties from corresponding miniature tensile tests.

Introduction

The shear punch test is a small specimen test technique for estimating uniaxial tensile properties from a transmission electron microscopy (TEM) disk [1-6] (and other sheet stock geometries). A 1 mm flat faced punch is driven through a TEM disk at a constant rate. In the past, some researchers, including the present authors, have assumed that crosshead displacement is approximately equal to the punch displacement, and the load has been plotted as a function of crosshead displacement. The resulting load versus crosshead displacement trace has many features common to a uniaxial tensile test trace including a region of linear loading, a yield point, a region of work hardening (or work softening), and an ultimate load [1,2]. Loads are converted to an effective[1] shear stress by dividing by $2\pi rt$ where "r" is the average of the radii of the punch and the receiving die, and "t" is the thickness of the specimen. The effective shear yield, defined as the point of deviation from linear loading, correlates well with uniaxial yield stress for a variety of materials [2]. The effective shear ultimate stress also correlates well with the uniaxial ultimate strength [2], and true uniform elongation can be correlated with shear punch test data [3].

Recent development of the shear punch test technique has focused on understanding the nature of the slope and intercept of the correlation between uniaxial yield and effective shear yield [7] as well as on identifying ways to reduce the material-to-material scatter in the correlation between uniaxial yield and effective shear yield [8]. Most recently, finite element analysis (FEA) was used to show that the compliance of test machines which have been used (and are typical for tensile tests) is much greater than the elastic compliance of a shear punch test specimen [8]. The FEA work suggested that by measuring displacement at the crosshead, the large test machine compliance would obscure the true load versus specimen displacement behavior. The FEA work also suggested that the correlation between uniaxial yield and shear yield would be improved if yield on a load versus punch tip displacement trace was measured at an offset shear strain in a manner analogous to measuring yield on a uniaxial tensile trace.

The conclusions of the FEA work were recently tested by constructing and using a low compliance shear punch test fixture which is fitted with a displacement measurement transducer that measures

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[1] The term "effective" is used because the stress state is known to not be pure shear [7,8]. However, for the sake of brevity, the term "effective" will be assumed for the remainder of this work.

displacement at approximately the top of the punch [9]. Shear punch tests were performed on a variety of materials, and the study firstly showed that there was indeed a large amount of compliance in the test fixture and load-train relative to the elastic compliance of a typical specimen tested in shear. A load versus punch displacement trace had a much different appearance than a corresponding load versus crosshead displacement trace due to the more direct measurement of specimen displacement. The load versus punch displacement traces always had a greater similarity to the corresponding uniaxial test traces. A particular benefit of using punch displacement traces was that it was now possible to measure shear yield at an offset shear strain in a manner analogous to that of a uniaxial tensile test where uniaxial yield is measured at an offset strain. Correlations between uniaxial yield and shear yield were made from crosshead displacement traces and punch displacement traces. Shear yield measured at a 1.0% offset shear strain on the punch displacement traces gave a slightly better correlation than did shear yield measured at deviation from linearity on the crosshead displacement traces.

In the present work, correlations between tensile properties and shear punch properties obtained using the new fixture are compared to correlations previously obtained using an older shear punch fixture with greater compliance [2]. The correlations examined were the yield correlation, the ultimate strength correlation, and the uniform elongation correlation.

<u>Experimental</u>

Testing

A schematic of the new shear punch fixture is shown in Figure 1. The key changes are the revised punch and the introduction of a displacement measurement transducer. The revised punch is estimated to be approximately 8 times stiffer than previous punches which were simply a 1 mm diameter pin, approximately 18 mm in length. Displacement was measured using a capacitive-based displacement measurement device (CDMD). The "stud" shown in Figure 1 is attached to the bottom half of the fixture, and serves as the reference point for the CDMD. As the CDMD is located inside of the "button", the CDMD roughly measures the displacement of the top of the punch relative to the surface on which the specimen rests, and therefore, test fixture compliance contributions come mainly from the punch only.

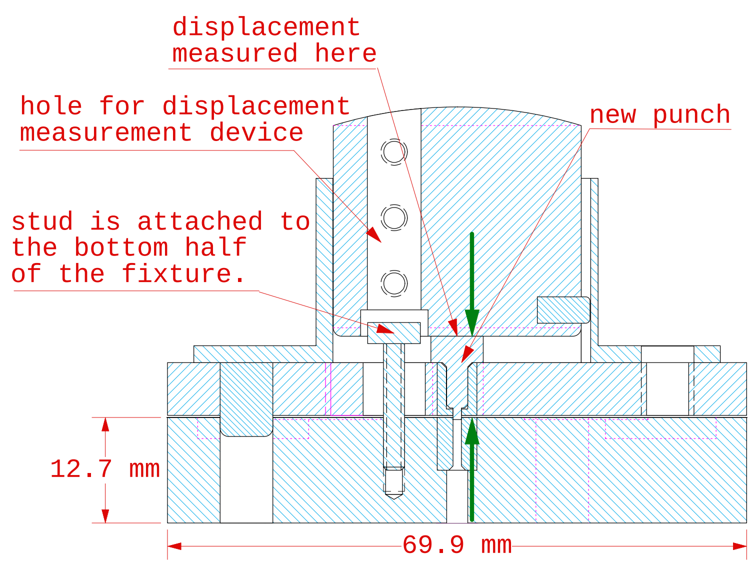

Figure 1. New shear punch fixture. Capacitive based displacement measurement probe measures its position relative to the top of the stud. Green arrows indicate the approximate displacement measurement reference points.

Table 1. Materials examined for this study and their thermomechanical treatments.

Alloy Class	Alloy	Thermomechanical Treatment
Al alloys	5000	0 (solution annealed), H38 (aged and cold-worked)
	6061	0 (solution annealed), T6 (aged)
Stainless steels	316 SS	2 different age and cold-work treatments
	HT9	2 different tempering treatments
Low carbon steel	1010	solution annealed, cold-worked
Brass	CDA-260	solution annealed, cold-worked
Cu alloys	$CuHfO_2$	cold-worked
	MZC3	precipitation strengthened

Materials and thermomechanical treatments used in this study are shown in Table 1. All specimens were electro-discharge machine (EDM) fabricated from sheet stock with a thickness of approximately 0.25 mm. A minimum of three shear punch tests and two tensile tests were performed per each unique combination of material and thermomechanical treatment.

The punch had a tip diameter of 0.98 mm while the receiving hole diameter was 1.04 mm. This gives a clearance, w, of 0.32 mm which is slightly larger than the previously used value of 0.25 mm. The initial shear strain rate, as calculated from

$$\dot{\varepsilon}_{rz} = \frac{1}{2}\frac{\dot{x}}{w} \tag{1}$$

where $\dot{x}$ is the punch displacement rate, was approximately $4\text{x}10^{-3}$ sec^{-1}. The factor of 1/2 in Eqn. 1 results from converting the shear strain to an engineering shear strain[2]. Displacement was simultaneously measured at the CDMD and at the crosshead. Load was converted to an effective shear stress by dividing by 2πrt where "r" is the average of the punch and receiving die radii, and "t" is the specimen thickness.

The S1 tensile geometry (1.2 mm gage width, 5 mm gage length) was used for the tensile specimens. The initial strain rate was approximately $1\text{x}10^{-4}$ sec^{-1}. Displacement was measured at the crosshead. Yield was measured at a 0.2% offset strain.

Correlation Development

Based on the FEA work [8], a 1.0% offset shear strain was used as the point at which shear yield strength (τ_y) was measured in the punch displacement traces from the new fixture. The shear yield values were empirically correlated with 0.2% offset uniaxial yield strength taken from the corresponding tensile tests. Shear ultimate strength (τ_m) was calculated at the point of maximum load on a shear punch test trace and was correlated with ultimate tensile strength. A strain hardening exponent, n_τ, calculated from the ratio of shear ultimate to shear yield, serves as a ductility parameter which was correlated with true uniform elongation from the corresponding uniaxial tensile tests [3]. The formula for calculating n_τ is given by:

[2] $\varepsilon_{rz} = \varepsilon_{zr} = 1/2(\gamma_{rz} + \gamma_{zr})$, $\gamma_{rz} = x/w$, $\gamma_{zr} = 0$

$$\left(\frac{n_\tau}{0.002}\right)^{n_\tau} = \frac{\tau_m}{\tau_y} \tag{2}$$

This equation results from combining the Power Law Strain Hardening equation with the equality that occurs between the strain hardening exponent and the true uniform elongation at the point of necking.

Results

It has been previously shown that the traces obtained from the new fixture more closely resemble the corresponding tensile traces than traces from older fixtures [9]. An example for a 5000 series Al alloy is shown in Figure 2 where it can be seen that the elastic loading slope of the punch displacement trace is steeper than that of the crosshead displacement traces. In general, it was observed that the greatest similarity between shear punch test traces and uniaxial tensile test traces occurred when the uniform elongation of the material was relatively low. This trend can be understood by considering that in a shear punch test, reduction in load bearing area is increasingly controlled by cutting of the material as punch displacement becomes very large. Thus, for materials which display low uniform elongation, cutting has a minimal effect on reduction in area in a shear punch test.

Yield Strength Correlation

The new correlation between uniaxial yield and 1.0% offset shear yield using the low compliance fixture is compared with a previously obtained correlation between uniaxial yield and shear yield at deviation from linearity using an older fixture with more compliance. These correlations are shown in Figures 3a and 3b, respectively, and are referred to as “2001” and “1994” correlations, respectively. Two sets of tensile tests and two sets of shear punch tests were performed to obtain the data, and many of the specimens for both correlations came from the same sheet stock. These materials can be inferred from the legends. The overall difference in the correlations is not great with the materials common to both correlations having the same relative positions on the plots. There is a difference in the slope of the correlations lines though, and this is due to differences in both shear yield values and uniaxial yield values for the tests conducted in 2001 and 1994.

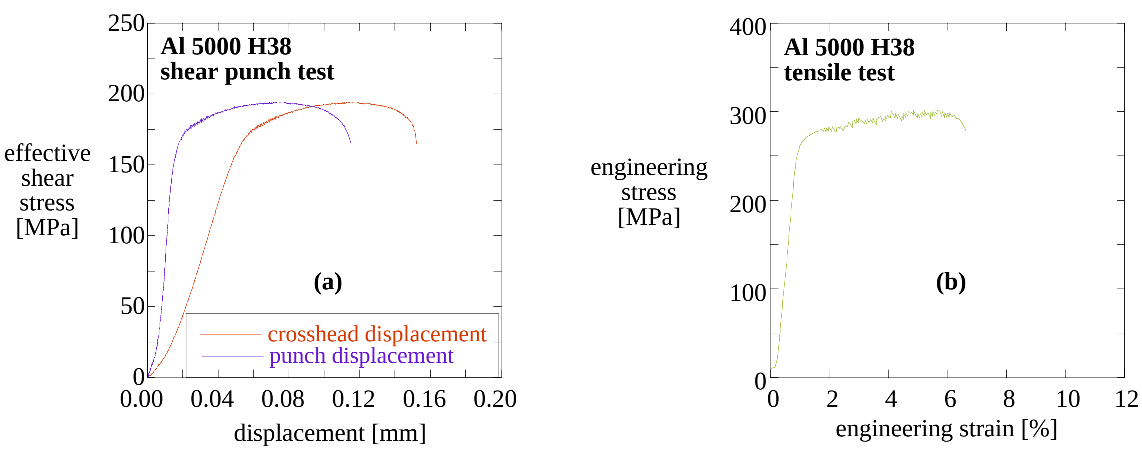

Figure 2. a) Shear punch and b) tensile traces for Al 5000-H38. Note that strain serrations are present in the shear punch test traces.

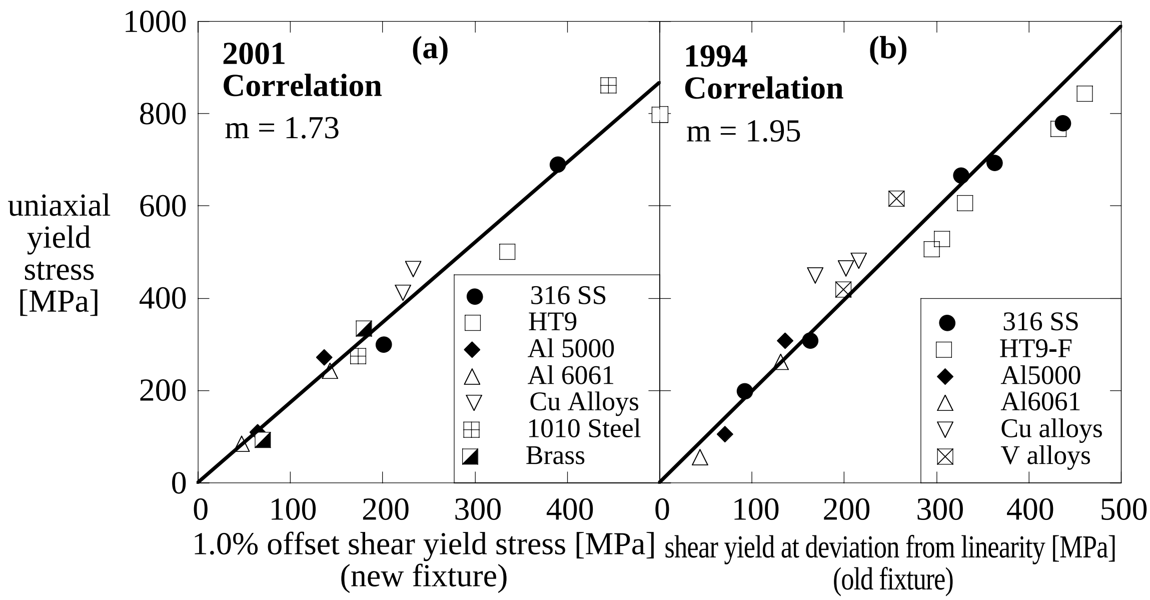

Figure 3. Correlation between uniaxial yield and shear yield for a) 1.0% offset shear yield on punch displacement traces using the new low compliance fixture and b) deviation from linearity on crosshead displacement traces using an older fixture with more compliance. Two sets of tensile tests and shear punch tests were performed to obtain this data. Many of the specimens for the two sets of tests came from the same sheet stock, and these can be inferred from the legends.

Ultimate Strength Correlation

The new correlation between uniaxial ultimate strength and shear ultimate strength is shown in Figure 4a and can be compared to the previous correlation shown in Figure 4b. For the materials which are present in both sets of correlations, the overall trends in the data are again similar, and a single trend line passing through the origin can adequately represent the data in both instances. However, the slope of the correlation lines is slightly different, and this is due to systematic differences in both the shear ultimate strength and the uniaxial ultimate strength values for the tests conducted in 2001 and 1994. The shear ultimate values for the tests performed in 2001 were, on average, slightly higher than those performed in 1994 while the uniaxial ultimate values for the tests performed in 2001 were on average slightly lower than the uniaxial ultimate values from the tests performed in 1994. It is logical to attempt to associate these differences with differences in test techniques, and there were some notable differences in test techniques between 2001 and 1994. For the shear punch tests, not only was a low compliance fixture used in 2001, but also the crosshead displacement rate was a factor of two lower. It would be expected that if the materials were strain rate sensitive, a lower crosshead displacement rate would lead to lower shear ultimate values, but in fact, the opposite occurred. Therefore, the reason for the slight increase in shear ultimate with the new fixture is not yet understood. For the tensile tests, the key difference is that a smaller specimen geometry was used for the tests performed in 1994. It has been observed that UTS values from miniature sheet type specimens are often higher than values from larger size sheet type specimens [10], so the differences in the tensile data can reconciled.

Ductility Correlation

Based on previous studies of the shear punch test, it was found that n_τ correlates best with the true uniform elongation measured in corresponding uniaxial tensile tests [3]. Shown in Figure 5a is the correlation between true uniform elongation and n_τ for shear punch tests performed using the low

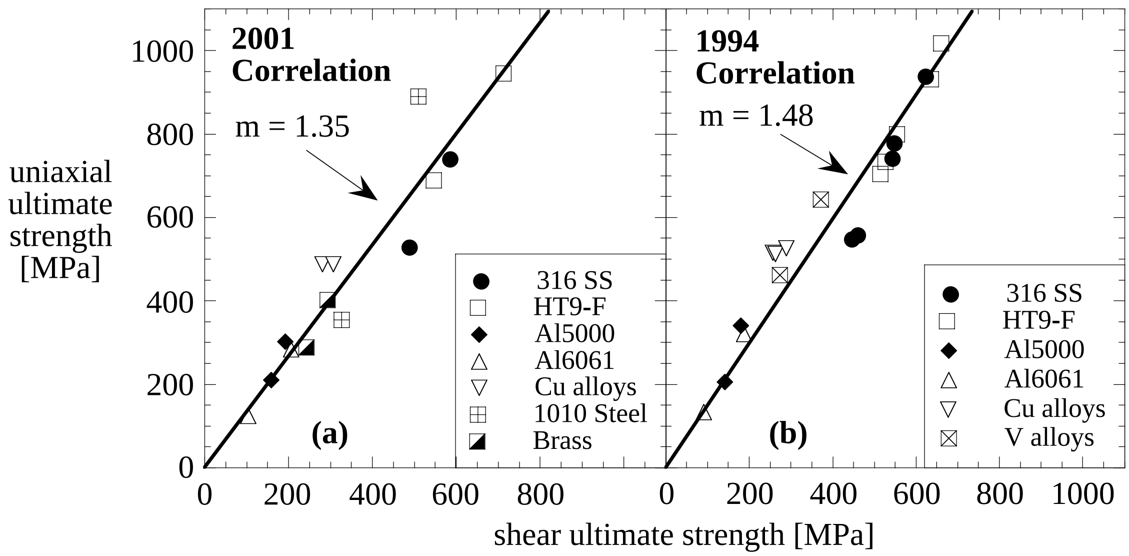

Figure 4. a) Correlation between uniaxial ultimate and shear ultimate using a reduced compliance fixture and b) a previous correlation between uniaxial ultimate and shear ultimate constructed using an older fixture with greater compliance. While some of the materials were the same for the correlations, both uniaxial and shear strength values came from two sets of tests with one set of tests performed in 1994 and the other set performed in 2001.

compliance fixture. Figure 5b shows a correlation between true uniform elongation and n_τ for shear punch tests performed in 1994 using an older fixture with more compliance. Overall, the correlations are largely similar with both correlations having approximately the same slope and same intercept. The values for the slope and the intercept have been previously explained [3]. The correlation constructed using the low compliance fixture does however, show more scatter about the trend line. As with the UTS correlation, there were small differences between the ε_u values and the n_τ values for the tests performed in 2001 and 1994 which led to increased scatter at the higher ductility values. Because there were differences in the values of both ε_u and n_τ for the two sets of tests, the increased scatter is not due to changes in the shear punch test technique alone but also the tensile test technique, again showing that the correlation is sensitive to the shear punch test and the tensile test technique.

<u>Discussion</u>

The FEA simulations of the shear punch test [8] suggested that the 2001 yield strength correlation would have much less scatter than the 1994 yield strength correlation, but in fact, the magnitude of the scatter was comparable. In a previous study of the new fixture, some of the predicted changes in the shear yield values from the FEA study were observed in the actual shear punch tests using the new fixture, but the changes were not as large as were predicted [9]. Perhaps this is because the finite element model did not incorporate deviations from ideal test behavior such as a slightly off-center punch or a slightly tilted punch. Or perhaps it is because some aspect of the deformation behavior of the test materials was not modeled as accurately as possible, such as the fact that the deformation behavior was assumed to be isotropic.

The high degree of similarity between the 2001 and 1994 ultimate strength correlations is understandable in that the ultimate load on a shear punch test can be determined unambiguously irrespective of the method by which displacement is measured. The one factor that could have made a difference between the shear ultimate strength values for the 2001 and 1994 tests is that the crosshead speed was a factor of two lower for the 2001 shear punch tests. This does not appear to have had an effect because if there

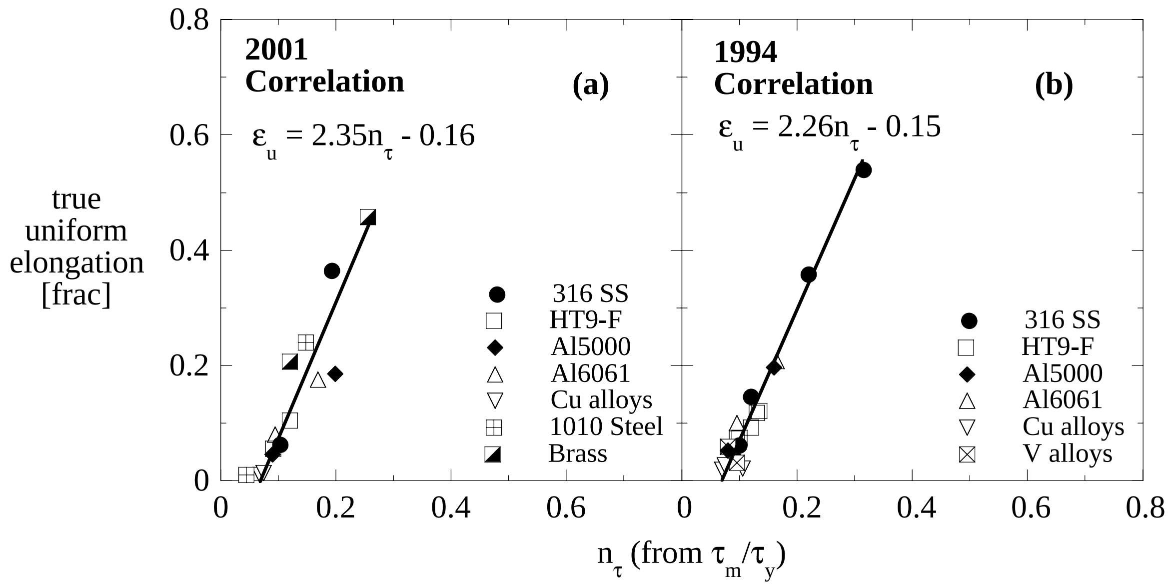

Figure 5. a) Correlation between true uniform elongation and n_τ using a reduced compliance fixture. b) A previous correlation between true uniform elongation and n_τ constructed using an older fixture with greater compliance. While some of the materials were the same for the correlations, the data came from two sets of tests with one set of tests performed in 1994 (higher compliance fixture) and the other set performed in 2001 (low compliance fixture).

were a strain rate effect, it should have been to reduce the shear ultimate values for the 2001 correlation relative to the 1994 correlation, but the opposite occurred.

As for the ductility correlation, it is understandable that the 2001 and 1994 ductility correlations are similar because both the shear yield and the shear ultimate values for the 2001 and 1994 correlations were only slightly different, and the shear punch ductility parameter is calculated from the ratio of these two values.

Because the correlations derived from the low compliance fixture are largely similar to the previously obtained correlations using an older fixture with more compliance, it would seem that there is no benefit to using a lower compliance fixture. However, there are other aspects of the shear punch test to consider. The low compliance fixture produces a test trace that better represents the deformation behavior of the specimen, and the test trace shape has a greater similarity to a corresponding tensile test. This is beneficial because it shows that the shear punch test reveals the same basic material behavior that would be observed in a tensile test. Further, by displacement at the punch, it has become possible to rationalize a shear strain in the early stages of a shear punch test which permits an unambiguous measurement of shear yield at an offset shear strain.

Summary and Conclusions

A new shear punch fixture with lower compliance and having a method for more direct measurement of crosshead displacement was constructed and evaluated. Yield strength, ultimate strength, and ductility correlations derived from shear punch tests using the new fixture along with corresponding tensile tests were compared to yield strength, ultimate strength, and ductility correlations obtained previously from shear punch tests using an older fixture with more compliance and a corresponding set of tensile tests. The correlations from the new shear punch fixture were largely similar to their respective correlations from the older shear punch fixture with more compliance. There were, however, some small differences in the new and old correlations, and these differences were found to be due to small changes in both the shear punch values and the tensile values.

While the low compliance fixture did not have a big impact on the correlations, the new fixture is an improvement over the older fixture because the new fixture produces a shear punch test trace that has a greater degree similarity to a corresponding tensile test trace, and with the new fixture, shear yield can be measured unambiguously at an offset shear strain in a manner analogous to a tensile test.

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