THE EFFECT OF TEST MACHINE COMPLIANCE ON THE MEASURED SHEAR PUNCH YIELD STRESS AS PREDICTED USING FINITE ELEMENT ANALYSIS - Mychailo B. Toloczko*, Katsunori Abe (Tohoku University, Japan), Margaret L. Hamilton, Frank A. Garner, and Richard J. Kurtz (Pacific Northwest National Laboratory)*

ABSTRACT

In previous research involving the use of the shear punch test, it was assumed that the displacement of the punch tip was only slightly different than the crosshead displacement. The present work explores this assumption and its ramifications by simulating the shear punch test with finite element analysis (FEA). The simulations suggest that punch tip displacement is much less than previously assumed, and that for the test frames which have been used, crosshead displacement is over an order of magnitude greater than punch tip displacement. This difference in displacements is thought to be due to test machine and punch compliance, and a simple elasticity calculation of the compliance of the punch, the test machine, and a specimen gives a result which is in agreement with the FEA simulations. The effect of using punch tip displacement on the observed effective shear yield stress was evaluated using FEA simulated shear punch tests on several different metals. Yield was measured at several different offset shear strains with a 1.0% offset shear yield strength measurement providing the best correlation with 0.2% offset uniaxial yield strength. When using the 1.0% offset shear yield values, the previously observed material-to-material variability in the tensile-shear correlation all but disappeared. Based on this work, it appears that the material-to-material variations in prior correlations between uniaxial yield strength and shear yield strength is due to a combination of large test machine compliance and material-to-material differences in the work hardening exponent.

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<u>Introduction</u>

The shear punch test is a small specimen test technique for extracting yield strength, ultimate strength, and uniform elongation values from metals using TEM disks [1-5]. It is a blanking operation where a 1 mm diameter flat faced cylindrical punch is driven through a TEM disk at a constant rate. A schematic of a shear punch test apparatus is shown in Fig. 1. Ideally, the load on the punch is measured as a function of punch tip displacement, but due to the difficulty in actually measuring the punch tip displacement, it has been previously assumed that crosshead displacement is approximately equal to punch tip displacement, and thus, the load on the punch has been measured as a function of crosshead displacement. Shear punch load versus crosshead displacement traces are similar in appearance to uniaxial tensile test traces. Yield is measured from these traces at deviation from linear elastic loading, and ultimate is measured at the peak load. The "effective" shear stress[1] is calculated assuming that the only stress generated during a test is a shear stress in the rz plane of a cylindrical coordinate system with z-axis parallel to the punch axis. Thus, the "effective" shear stress is:

$$\sigma = \frac{P}{2\pi r t} \tag{1}$$

where P is the load on the punch, r is the average of the punch and receiving die radii, and t is the specimen thickness. True uniform elongation is estimated from the ratio of the shear ultimate strength to the shear yield strength [3].

In a recent FEA based study of the shear punch test [6], the authors of the study observed that, 1) the elastic loading slope of an FEA generated load versus punch tip displacement

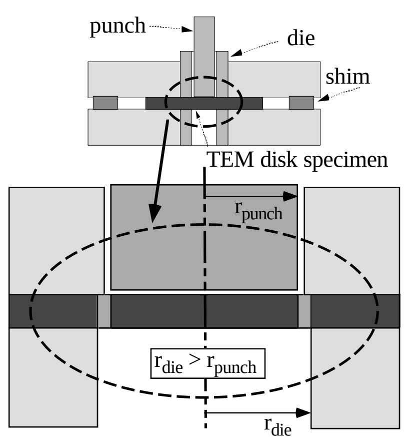

Figure 1. Sketch of the shear punch fixture.

[1] For the sake of brevity, the "effective shear stress" will simply be called the "shear stress".

trace was much steeper than observed in real shear punch tests, 2) the strain hardening behavior was much different than observed in real shear punch tests, and 3) the yield point observed in the FEA simulations was lower than what was observed in real tests. Since the authors were focused on other results obtained from the FEA simulations, the aforementioned differences between the FEA simulations and the real test traces were not given any further consideration.

The present work represents an effort to examine those aspects of the FEA simulated shear punch test which were not examined in the first paper [6]. It was determined that the compliance of a typical mechanical properties test frame is much greater than the elastic compliance of a typical shear punch test specimen (when loaded in the shear punch test). It was this large test machine compliance which led to the difference in the shape of a real shear punch test trace and an FEA generated shear punch test trace. It was found that the correlation between shear yield strength and ***uniaxial*** yield strength improved when using shear yield strength values obtained from load versus punch tip traces generated in FEA simulations of the shear punch test.

Experimental: The Finite Element Analysis Simulation

The MARC finite element analysis software was used to simulate the shear punch test. To reduce computing time and costs, an axisymmetric mesh was utilized and is shown in Fig. 2. There are three main components to the mesh: the specimen, the punch, and the receiving

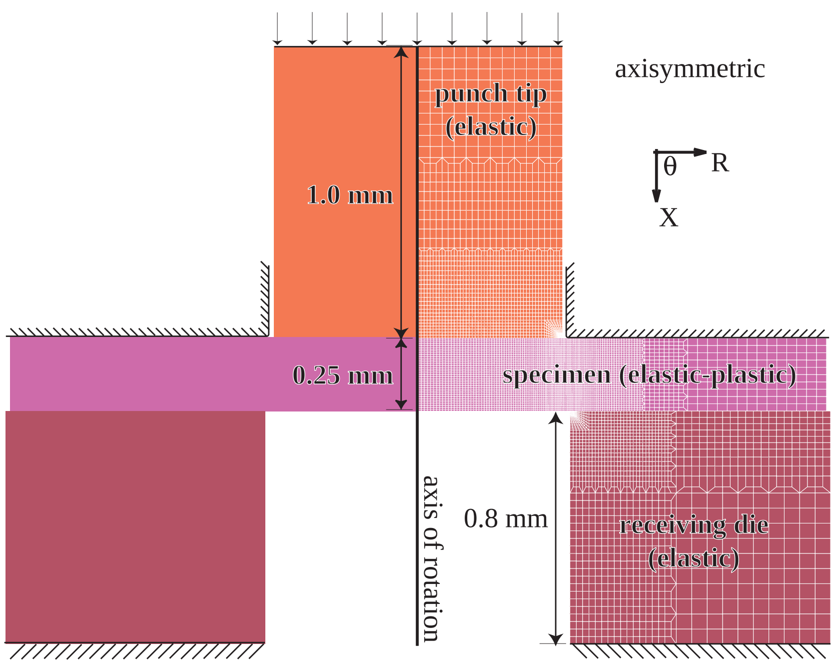

Figure 2. Sketch of the mesh used in the present study.

die. The specimen was modeled as elastic-plastic. In an effort to make the simulation as realistic as possible, the punch and the receiving die were modeled as elastic. This allows for a small amount of elastic deformation in these components which alters the stress distribution in the specimen mesh[2]. The specimen has a thickness of 0.25 mm and a diameter of 3 mm. The mesh consisted of 4340 elements. The punch diameter is 1.016 mm. In real shear punch tests, the punch is about 20 mm in length, but for the simulations, only 1 mm of the 20 mm length was modeled. The diameter of the receiving die is 1.0414 mm, and as with the punch, only a small portion of the length of the entire receiving die was modeled (0.8 mm). The lengths of the punch and the die were chosen so that the stresses at the top of the punch and the bottom of the die were fairly uniform. This guarantees that the stress concentrations at the punch tip and die tip can relax in the same manner which they do in a real test. The punch and the receiving die meshes were composed of 1527 and 1395 elements respectively. As with any finite element analysis, material properties must be inserted into the model. For this simulation, the punch and the receiving die were assigned the elastic properties of BCC steel (E = 200 GPa, ν = 0.28). The specimen was assigned the uniaxial deformation behavior of several different materials of interest as described in the next paragraph. The FEA boundary conditions were as follows:

1) Translations in the radial direction were prevented because the model is axisymmetric.
2) The bottom of the receiving die was held stationary in the axial direction.
3) An immovable boundary was placed in contact with a portion of the top of the specimen to simulate the presence of the upper-half of the shear punch fixture. No clamping force was applied to the specimen with this boundary condition.
4) Friction between the components was set equal to zero. The previous FEA based study has shown the effect of friction between components to be minimal [6].

During a simulation, the top of the punch was moved at a constant rate. Under the assumption that real shear punch tests are performed in the strain rate independent realm, the FEA simulations were run in static mode. Due to the difficulty in simulating the cutting and failure behavior which occur in a real shear punch test, the FEA simulations were run to only a small amount beyond yield.

Simulated shear punch tests were performed on several different materials. Different materials were “tested” by assigning true stress versus true plastic strain data and elastic

[2] Simulations using a rigid punch and receiving die were also performed but are not reported here. By comparing these results using a rigid punch and receiving die to the results obtained using an elastic punch and receiving die, it was found that using an elastic punch and receiving die significantly altered the stress state in the FEA specimen (reduced stress concentrations) and had a significant influence on the apparent transition from linear elastic loading to plastic deformation in a load versus punch tip displacement trace.

deformation properties from different materials to the specimen elements. The true stress versus true plastic strain data were obtained from miniature tensile tests performed on 316 SS, HT9 (a 12Cr-1Mo martensitic stainless steel), several dispersion strengthened copper alloys, a precipitate strengthened copper alloy, vanadium alloys, and aluminum alloys. A brief summary of the materials can be found in Table 1. Further details about these materials can be found in Ref. 2.

During a simulation, the MARC program keeps track of the load on the punch and the displacement of the top of the punch. To obtain the punch tip displacement, it was necessary to run simulations using a rigid punch and receiving die. By comparing the elastic loading obtained from a rigid component test to an elastic component test, it was possible to measure the compliance of the punch and receiving die. This compliance value was then used to estimate the punch tip displacement as a function of the displacement at the top of the punch using the following formula:

$$x = x' - PC' \tag{2}$$

where x is the punch tip displacement, x' is the displacement at the top of the punch, P is the load on the punch, and C' is the measured compliance of the punch and receiving die. Using the calculated punch tip displacement data, load versus punch tip displacement traces were created.

FEA generated shear stress versus punch tip displacement traces were compared to shear stress versus crosshead displacement traces obtained from real shear punch tests. These shear punch tests were performed several years ago using a machine with a compliance that is typical of that for tensile tests. Further details of these shear punch tests have been published [2, 7].

Table 1. Materials and thermomechanical treatments studied in this work.

Alloy	Thermomechanical Treatments
Al 5052	0 (solution annealed), H38 (aged and CW)
Al 6061	0 (solution annealed), T6 (aged)
316	SA, 20% CW, 40% CW, 2 age/CW treatments
HT9	normalized, 4 different tempering treatments
316, 316L	SA, CW
CuAl25	50% CW
MZC-3	aged and cold-worked
$CuHfO_2$	20% CW
V-5Cr-5Ti	950°C/1h/furnace cool
V-3Ti-0.3Si	1150°C/1h/furnace cool

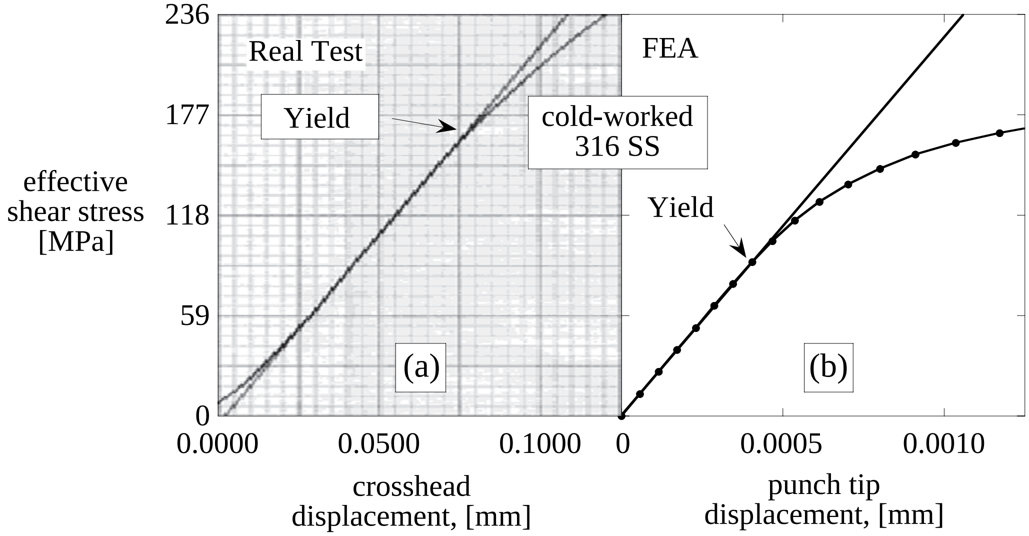

Figure 3. a) Shear stress versus crosshead displacement trace for a real shear punch test of a cold-worked 316 SS, and b) shear stress versus punch tip displacement trace for an FEA simulated shear punch test on the same steel.

Results and Discussion

Compliance

While simulated tests were performed on many different materials, the results can be most efficiently conveyed by showing the behavior of one combination of material and thermomechanical treatment, namely using one of the cold-worked 316 SS conditions. Fig. 3a shows a shear stress versus crosshead displacement trace obtained from a real shear punch test on a cold-worked 316 SS specimen, while Fig. 3b shows a shear stress versus punch tip displacement trace obtained from an FEA simulation of a shear punch test on the same material. The key aspect of this comparison is that the elastic loading slope for the FEA simulation is 2 orders of magnitude steeper than the elastic loading slope of the real shear punch test (look at the x-axis scales in figures). This result mirrors the result obtained in the previous FEA based study of the shear punch test [6]. Since the main difference between an FEA simulation and a real shear punch test is the location at which displacement is measured, it is reasonable to assume that this is leading to the dissimilar traces. This could be determined by measuring the compliance of the test machine, but performing such a compliance measurement is not a simple task because of the geometry of the shear punch test.

An alternative method for obtaining the test machine compliance is to calculate it directly using the dimensions of the major components in the load-train of the test machine and using Young's modulus. First, consider the relative compliance of the punch and a specimen. The punch which was used for the shear punch tests has a diameter of 1.016 mm and a length of approximately 20 mm. Assuming a Young's modulus of 200 GPa, this leads to a compliance of approximately 1.2×10^{-4} mm/N. This can be compared to the calculated elastic compliance of a specimen. For a shear modulus of approximately 75 GPa (steel), and for a 0.25 mm thick specimen under an idealized shear deformation shown in Fig. 4, the elastic compliance of the specimen due to shear deformation is estimated to be 2×10^{-7} mm/N. Due to the way load is applied during a shear punch test, a specimen is also compressed. Assuming the majority of the compression occurs in an annular region with in radius of 0.85 mm and outer radius of 1.15 mm, the compliance due to the compression is estimated to be approximately 6.6×10^{-7} mm/N. The total estimated compliance of a specimen is then approximately 8.6×10^{-7} mm/N. Hence, the estimated ***punch*** compliance is approximately a factor of 140 greater than the estimated elastic compliance of a steel specimen. An idealized calculation of the compliance of the remainder of the load-train would increase this ratio to approximately 150. Thus, these simple elasticity calculations tend to confirm the results obtained by comparing the elastic loading observed in the FEA simulations to the elastic loading observed in real shear punch tests.

Following the idea that the differences in the traces for the FEA simulations and the real shear punch tests is due to test machine compliance, a compliance was added to the FEA punch tip displacement data. By adding a compliance, the punch tip displacement was converted to a hypothetical crosshead displacement. The equation which describes this hypothetical crosshead displacement is

$$\delta = x + PC \tag{3}$$

where δ is the hypothetical crosshead displacement, x is the displacement of the punch tip, P is the load on the specimen, and C is the estimated test machine compliance (including the punch). C was found by comparing the elastic loading slope in shear punch test traces obtained from real tests and from FEA simulations. For the 316 SS trace in Fig. 3a, C is approximately 5.5×10^{-4} mm/N. The resulting shear stress versus hypothetical crosshead displacement trace is compared to the real test trace in Fig. 5. The FEA generated trace has been transformed into a trace that looks nearly identical to the real trace. The yield point estimated from the transformed FEA trace is 165 MPa whereas the yield point estimated from the real test trace is 163 MPa. This further confirms the idea that crosshead

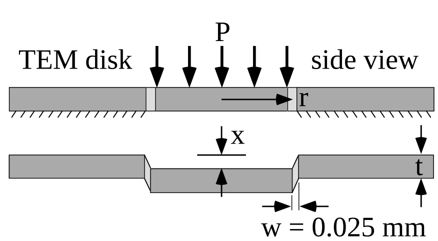

Figure 4. Idealized deformation during a shear punch test.

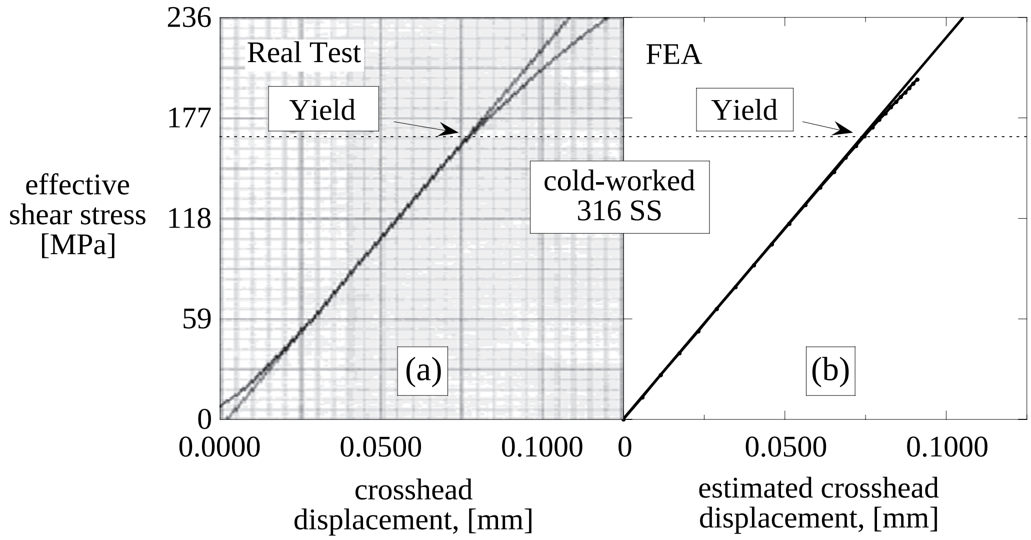

Figure 5. Comparison of a real trace and an FEA simulated trace where the FEA punch tip displacement data has been converted to a hypothetical crosshead displacement data using Eq. 3.

displacement measured in real tests is much larger than the actual punch tip displacement. It also shows that a large amount of compliance can strongly alter the appearance of a load versus displacement trace.

Shear yield stress measurement and correlation to uniaxial yield stress

For the shear punch tests performed to date, load has been measured as a function of crosshead displacement. Shear yield has been measured from these traces at deviation from apparent linear elastic loading. Shear yield values measured in this way have, in general, correlated very well with uniaxial tensile data [1-3, 5]. However, there is some material-to-material variability in the yield correlation. To examine the effect of test machine compliance on the observed shear yield stress, shear yield stress was measured from the FEA generated shear stress versus punch tip displacement traces. Since punch tip displacement data were used, it was deemed reasonable to re-assess the method by which shear yield is measured. Besides simply measuring the shear yield at deviation from linear elastic loading, the shear yield was also measured at an “offset shear strain” in a manner analogous to the 0.2% offset uniaxial yield stress measurement technique. The (fractional) shear strain was calculated using the following formula:

$$\varepsilon_{rz} = \frac{1}{2}\frac{x}{w} \tag{4}$$

where w is the difference in the punch and receiving die radii (Fig. 4). The factor of 1/2 results from using the tensor definition of shear strain. The optimum offset shear strain was chosen based on how well the shear yield values correlated with real 0.2% offset uniaxial strain measurements. Shear yield measured at offset shear strains ranging from 0% (deviation from linearity) to 1.0% were tried, and the correlations resulting from these two extremes are shown in Fig. 6a and Fig. 6b. It is clear that measurement of shear yield at 1.0% offset shear strain resulted in the best correlation with the data collapsing nearly perfectly onto a straight line.

Fig. 6b can be compared with Fig. 7a and Fig. 7b which show the yield correlation when measuring shear yield at deviation from linearity using either (a) real shear stress versus crosshead displacement traces or (b) FEA generated shear stress versus estimated crosshead displacement traces. The 1.0% offset shear yield measurements produce a noticeably better correlation (Fig. 6b) compared to shear yield measured at deviation from linearity (Fig. 7a and Fig. 7b). Two tangible factors likely contribute to the improvement in the correlation. First, shear stress versus punch tip displacement traces provide a much more accurate representation of the stress-strain relationship in a material during a shear punch test. And second, with this improvement, it is possible to measure the shear yield stress in a manner similar to the method by which yield is measured from uniaxial tensile test traces. The fact that an offset shear strain resulted in the best correlation is reasonable because it is known that the relative uniaxial yield strength of different materials depends on what offset strain is used when measuring the yield point[3] [8]. A somewhat intangible factor

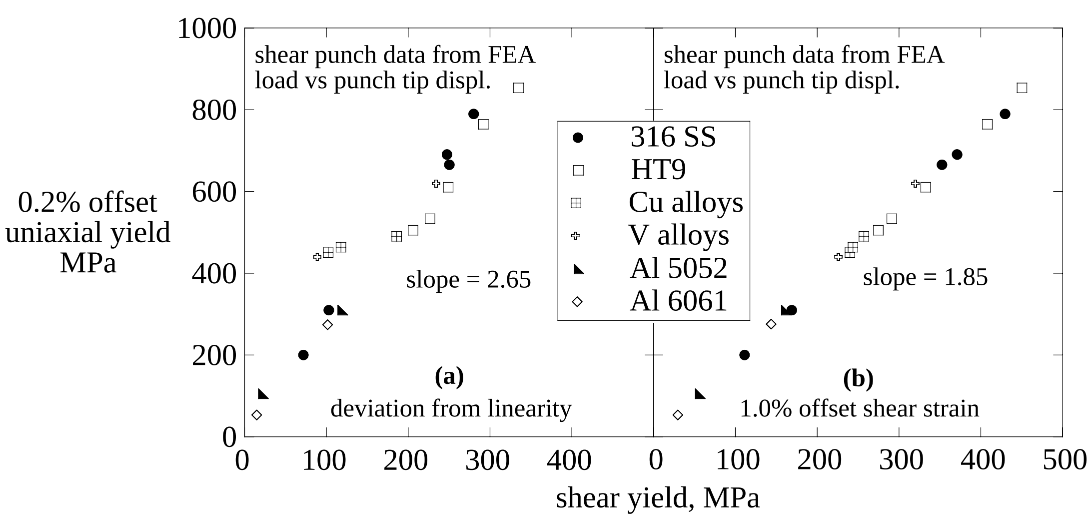

Figure 6. Comparison of correlations where shear yield was either measured (a) at deviation from linearity in an FEA shear stress versus punch tip displacement trace or (b) at a 1.0% offset strain in an FEA shear stress versus punch tip displacement trace.

[3] The relative variation is because, in general, different materials exhibit different strain hardening behavior. Some materials exhibit relatively little strain hardening, and the yield stress increases very little with increases in offset strain while other materials exhibit high strain hardening, and the yield stress increases very rapidly with increasing offset strain.

which may also contribute to the improvement in the correlation is material strain rate effects. During the FEA simulations, the materials were tested in static mode where strain rate effects are not present. In comparison, during a real test, there may be material strain rate effects. With a large amount of test machine compliance, the displacement rate of the punch tip will be time dependent. Relative to the speed of the crosshead, the punch tip speed is given by:

$$v_x = v_\delta - C\frac{dP}{dt} \tag{5}$$

were v_x is the punch tip speed and v_δ is the crosshead speed. During elastic loading, dP/dt is constant, and the difference in speed between the crosshead and the punch tip will also be constant. However, once the loading trace goes non-linear, dP/dt will no longer be a constant, and the difference in speeds will change. Since dP/dt will decrease, the punch tip will move at a faster and faster speed. The peak punch tip speed will be reached at maximum load, and at this point, the punch tip speed will equal the crosshead speed. Thus, during the course of a test where a large amount of test machine compliance is present, the punch tip speed may increase by several orders of magnitude. It therefore seems quite plausible that there may be strain rate effects in real tests when a large amount of test machine compliance is present. For a large amount of test machine compliance, it is thought that because materials usually have a positive strain rate exponent and because the punch tip speed increases during a test, the observed loads would be artificially high. Since the strain rate exponent is temperature dependent, this effect may be magnified at elevated test temperatures.

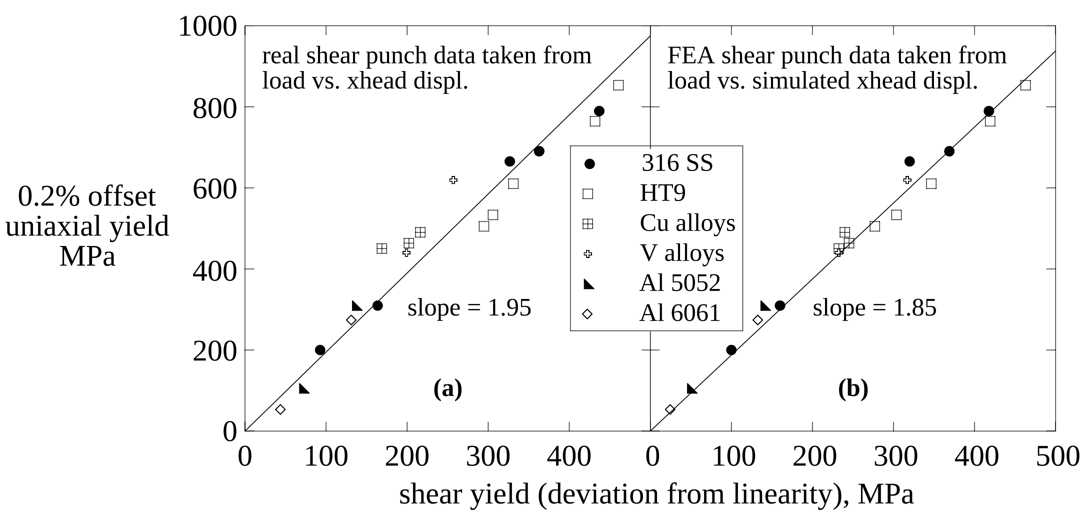

Figure 7. Comparison of correlations where shear yield was measured at deviation from linearity using either (a) real shear stress versus crosshead displacement traces or (b) using FEA generated shear stress versus simulated crosshead displacement traces.

The improvement in the correlation between uniaxial yield strength and FEA based shear yield strength suggests that the correlation between uniaxial yield strength and ***real*** shear yield strength measurements could be improved if a shear punch test fixture which more directly measures punch tip displacement could be constructed. Such a fixture has been designed and constructed, but evaluation and testing could not be completed in time for this paper.

Summary and Conclusions

In a previous finite element analysis based study of the shear punch test, it was noted that shear stress versus punch tip displacement traces obtained from FEA simulations looked much different than that obtained from real tests. The results of the present study suggest that the apparent differences in the original FEA traces and real traces is due to an incorrect assumption that crosshead displacement is nearly equal to punch tip displacement. It appears that punch tip displacement during a shear punch test is much smaller than previously assumed, and that an amount of test machine compliance which is considered normal for a tensile test is unacceptably large for a shear punch test if displacement is to be measured at the crosshead.

The present study also suggests that the previously observed material-to-material variability in the correlation between shear yield strength and uniaxial yield strength is due to a combination of large test machine compliance and material-to-material variability in the work hardening exponent. By measuring shear yield at an offset shear strain in FEA generated shear stress versus punch tip displacement traces, the correlation between uniaxial yield and FEA derived shear yield strength was significantly improved. A new shear punch fixture which eliminates most test machine compliance has been constructed, and evaluation of the new fixture in progress.

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