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Abstract

Small and shear punch testing are promising techniques that can be applied as virtually non-destuctive tools to monitor in-service components and maximise the amount of information that can be obtained from limited in situ material; several mechanical properties can be determined at critical locations of a component with no need for repair welds. Using flat (shear) and hemispherical-shaped (small) punches to push into thin disc-shaped specimens, mechanical properties can be measured. In engineering design, conventional uniaxial test data are used and thus investigations into how small scale test data compare to traditional,standardised, test data are required.

In this work, small and shear punch testing have been carried out in order to evaluate mechanical properties of precipitation hardened steel 17-4PH. Tensile properties, i.e. yield and ultimate tensile strengths, for this material have previously been determined from hardness data and correlations were made between these data and information obtained from the punch tests. For the shear punch test data, a method using a 0.2% offset criterion in conjunction with normalised shear-punch curves was used to measure the shear yield strength; linear correlations between shear data and tensile data was established for yield and ultimate strengths. **Add something else about small punch test data.**

Introduction

With the advent of next generation nuclear power systems including GEN IV, Small Modular Reactors (SMRs) and fusion reactors, there is a drive to develop a better understanding of the effects of irradiation damage on key structural materials. Given that relatively large volumes of material are required to carry out conventional mechanical characterisations, small specimen test technologies are crucial when material availability is limited (i.e. during material development) or when removing material from in-service components. Removal of in situ material is not only challenging, but also expensive; the procedure for extracting standard UAC specimens often requires a subsequent repair weld, which may itself cause degradation in the mechanical properties of the material, thus is typically minimised.

Small and shear punch tests are examples of test techniques that utilise miniature specimens. They have the advantage in that they can be applied as a virtually non-destructive tool to monitor service-induced degradation of structural components using scooped out specimens without damaging their structural integrity. Given that conventional uniaxial test data are used in engineering design, there is a need to understand whether a correlation can be established between punch data and conventional uniaxial data. Reasonable correlations have been observed between values of shear/tensile yield and shear/tensile strengths estimated from punch tests and mechanical properties determined from uniaxial tests [1] [2] [3] [4] [5] [6] [7].

This investigation has been undertaken to demonstrate the suitability of using small and shear punch testing to evaluate the mechanical properties of 17-4PH, a precipitation hardened steel. After solution annealing followed by quenching, 17-4PH can be heat treated to different temperatures to give a wide range of mechanical properties [8]. Two typical heat treatments for this alloy are 480 °C for 1 hour, providing maximum hardness and strength, and 590 °C for 4 hours, which improves the alloys toughness and ductility. In the present work, correlations between shear and tensile properties obtained from punch testing and mechanical properties obtained from hardness data have been obtained and comparisons have been made to correlations presented in the literature for materials exhibiting a range of tensile strengths.

Experimental

Materials

The as-received material was an 8 mm diameter rod of 17-4PH stainless steel. The chemical composition is given in Table 1. A solution treatment at 1040 °C for 1 hour (followed by an oil quench) was applied to dissolve any precipitates and form a single-phase microstructure; only precipitates formed during subsequent hardening treatments will be present in the final material. The rod was then sectioned to produce 0.70 mm thick disc specimens; specimens were then heat treated at 480 °C for 10 minutes, 30 minutes, 1 hour and 2 hours and 590 °C for 10 minutes, 20 minutes, 30 minutes, 2 hours and 24 hours.

Table 1. Concentrations of the main elements of as-received 17-4 PH.

Element	Fe	Cr	Ni	Cu	Mn	Si	Nb	Mo	Co	V	N	C
	74.2	16.42	4.41	2.9	0.75	0.67	0.15	0.08	0.06	0.05	0.12	0.06

The test specimens were ground to a final thickness of 0.500 mm (±0.005 mm) using P1200 silicon carbide grinding paper. Specimen thicknesses were measured at four positions around the perimeter at 90 ° intervals from each other and one from the centre and an average value was taken.

Yield and ultimate tensile strengths have been determined from Vickers hardness (H_v) measurements using correlations given by Yrieix and Guttman [12] for a range of as-received martensitic steels and aged 17-4PH steel. These relationships are outlined below.

$$\sigma_y = 3.7H_v - 317.7$$

Equation 1

$$\sigma_{UTS} = 3.1H_v - 23.9$$

Equation 2

Punch Test Setups

All punch tests were carried out using the experimental rig shown in Figure 1. During small punch testing a disc specimen was placed in the recess of the receiving (lower) die, across which was placed an upper die; both parts of the tool were clamped together and the load was transferred onto the specimen by the punch under a constant displacement until specimen fracture. During this test, the relationship between instantaneous punch load, F, and specimen deflection, δ, can be examined. The hemispherical tipped punch has a diameter of 2.50 mm ± 0.001 mm and the receiving die a diameter of 4 ± 0.01 mm. The chamfer edge of the receiving die is l=0.2 mm x 45°.

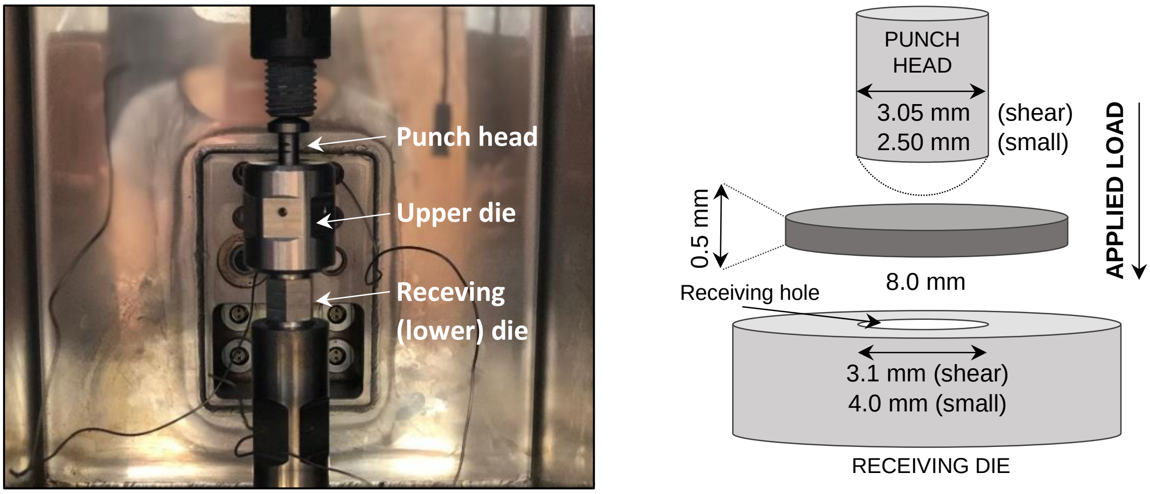

Figure 1. Small and Shear Punch Test Setup.

Shear punch testing is based on a blanking operation and was carried out using the same experimental rig as small punch testing. During testing, a disc specimen was loaded under constant displacement using a flat-tipped punch head and a circular disc was punched from it. Similarly to the small punch test, the relationship between instantaneous punch load and specimen deflection can be examined. The flat end punch has a diameter of 3.05 mm and the receiving die a diameter of 3.10 mm. All small and shear punch tests were performed at room temperature under a displacement rate of 0.25 mm/minute.

Data Analysis

Shear Punch Test

An example of a punch load-deflection curve obtained from shear punch testing is shown in Figure 2; the characteristics that it has in common with a conventional uniaxial tensile test are highlighted: a linear elastic region, the onset of plasticity, a maximum load and a reduction in load as the specimen continues to extend. Displacement has been normalised to specimen thickness, d/t, and the method by which the yield shear stress was determined is given in the inset plot; analogous to finding the 0.2% offset tensile yield strength from a stress-strain curve generated from a conventional uniaxial tensile test, an offset line parallel to the linear portion of the shear punch test curve was used.

Shear stress, τ_e, can be calculated using the following expression [9]:

$$\tau_e = \frac{P}{\pi D_{avg} t}$$

Equation 3

where P is load, D_{avg}=(D_p+D_d), D_p is the punch diameter, D_d is the lower die receiving hole diameter and t is the thickness of the specimen.

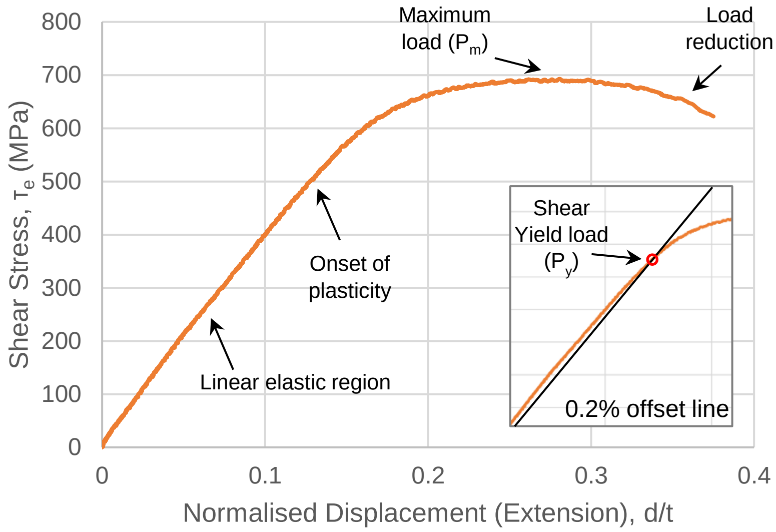

Figure 2. Typical shear punch test curve. Data obtained from a shear punch test of 17-4PH stainless steel solution treated at 1040 °C for 1 hr and heat treated at 590 °C for 2 hr.

Shear yield strength and maximum shear strength values, $\tau_{e(y,m)}$, obtained by shear punch testing can be correlated to tensile yield strength and ultimate tensile strengths $\sigma_{y,UTS}$, using the relationship given in Equation 4.

$$\sigma_{y,UTS} = m \cdot \tau_{e(y,m)} - \tau_0$$

Equation 4

When corresponding sets of shear strength and tensile strength data are plotted, they have been shown to fall on a straight line [1] [2] [4] [5]; a linear regression can be performed to obtain constant *m* and x-axis intercept, τ_0, in Equation 4. τ_0 is associated with the shear punch test but not the tensile test [10] and has originally been ascribed a result of the friction between the punch die and the specimen [11].

Small Punch Test

An example of a small punch load-displacement curve obtained from small punch testing is shown in Figure 3. Similarly to the shear punch test curves, the small punch load-deflection curves have characteristics in common with the tensile test. Four distinct regions are observed: (I) elastic bending deformation, (II) plastic bending, (III) plastic membrane stretching and (IV) plastic instability [13]. Given the complexity of the stress state that develops during testing, the work carried out so far in the literature has focused on establishing empirical relationships between different macroscopic mechanical properties and certain characteristic points of the load-displacement curves.

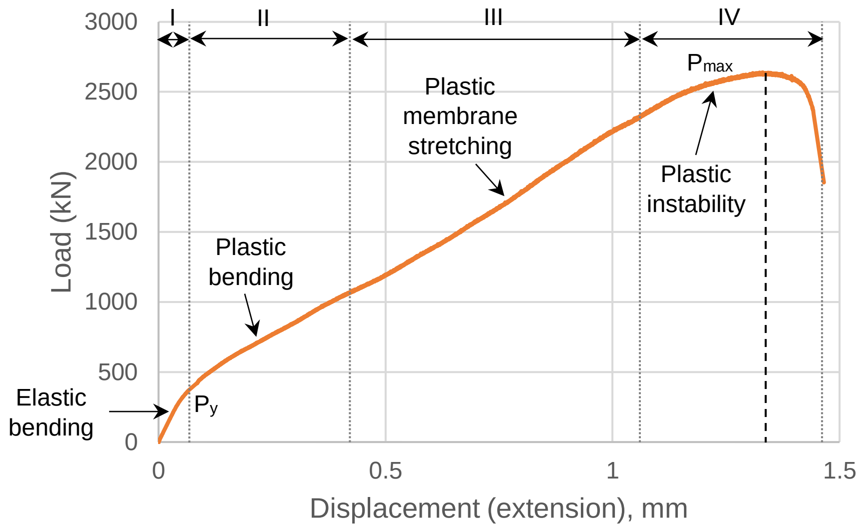

Figure 3. Typical small punch test curve. Data obtained from a small punch test of 17-4PH stainless steel solution treated at 1040 °C for 1 hr and heat treated at 590 °C for 24 hr.

In this study, the uniaxial tensile yield stress has been estimated using the following relationship of the type,

$$\sigma_y = \alpha_1 + \alpha_2 \left(\frac{P_y}{t_0^2} \right)$$

Equation 5

where α_1 and α_2 are constants, t_0 is the thickness of the specimen and P_y is the load at the beginning of the plastic bending regime. σ_y is expressed as the dependences of the yield stress on the parameter P_y/t^2 because the parameter P_y/t^2 eliminates any differences in disc specimen thicknesses on load P_y. P_y is calculated using the methodology given in the CEN Workshop Agreement [11]; P_y is given as the crossing point of two tangents defined in the elastic regime (Stage I) and plastic regime (Stage II).

The following correlations have been widely used for the estimation of the ultimate tensile strength, σ_{UTS}.

$$\sigma_{UTS} = \beta_1 + \beta_2 \left(\frac{P_{max}}{t_0^2} \right)$$

Equation 6

$$\sigma_{UTS} = \beta_1 + \beta_2 \left(\frac{P_{max}}{t_0 u_m} \right)$$

Equation 7

where P_{max} is the maximum force applied during SP testing and u_m is the corresponding deflection (measured at the centre of the specimen). However, the assumption that P_{max} in an SPT curve is similar to σ_{UTS} in a uniaxial stress-strain curve may not be fully justifiable; in small punch tests, microcracks have been observed prior to reaching P_{max} [12] whereas in uniaxial tensile testing, no such cracking occurs. In a conventional stress-strain curve, as discussed by Kumar et al. [13], the region corresponding to ultimate tensile strength correlates to the start of necking, normally beginning once maximum load is reached. At this point, the increase in stress due to a decrease in specimen cross-sectional area becomes greater than the increase in load carrying ability of the material due to strain hardening.

In a small punch test, however, the point at which necking, or localised deformation, begins is considered to be much earlier than in the conventional tensile test and attempts have been made to correspond necking to a point in Zone III of the load-displacement curve.

Recent studies [14] [15] have discussed an alternative method to incorporate less ductile materials for correlating force, P_i, to the ultimate tensile strength at a much lower displacement, v_i, in the force-displacement curve. Using the Altstadt method (ALT), the following correlation has been proposed [14]:

$$\sigma_{UTS} = \beta_{ALT}\left(\frac{P_i}{t_0^2}\right)$$

Equation 8

F_i (in N) is extracted from the test data at a displacement value, v_i, of 0.645 mm and a correlation factor, β_{ALT}, has been defined as 0.183 for a range of materials with different tensile strengths and ductilities [15].

Results and Discussion

Shear Punch Test

Figure 4 compares shear punch test curves for the 17-4PH specimens in each condition. Using Equation 3, punch load was converted to shear stress and the punch displacement was normalised to the specimen's initial thickness in order to eliminate any effect of specimen gage. It is evident that the different annealing times and temperatures have resulted in wide ranges of yield and ultimate strength levels, which are required in order to identify a shear-tensile correlation.

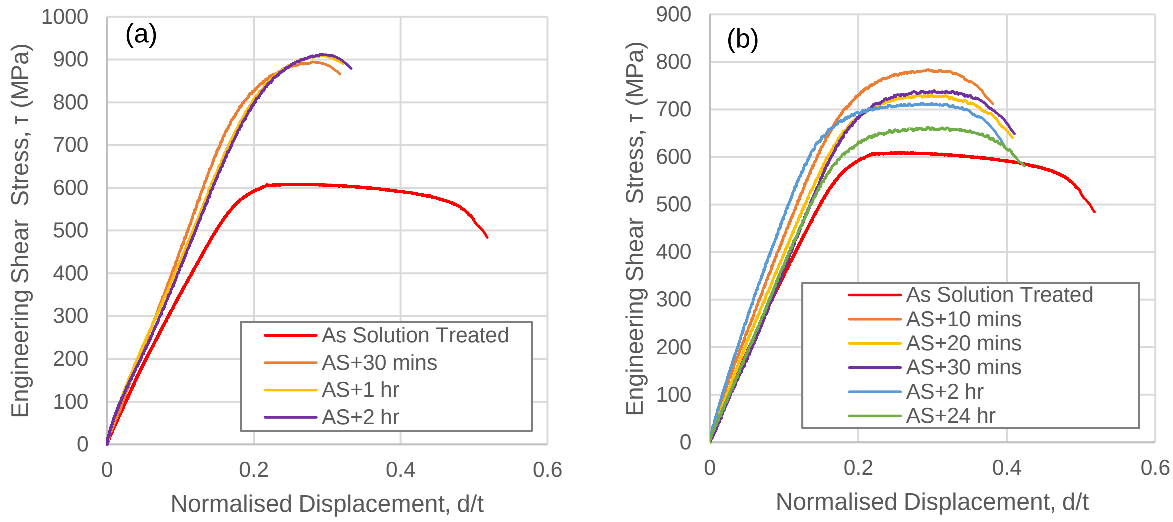

Figure 4. Shear punch test curves for 17-4PH solution treated at 1040 °C for 1 hr and heat treated at (a) 480 °C for times ranging 30 mins to 2 hr and (b) 590 °C for times ranging 10 minutes to 24 hr.

In Figure 5, the variation in Vickers hardness, shear yield stress and ultimate shear stress of the specimens at both heat treatments as a function of holding time is shown. Hardness data are taken from Yeli et al. [8]. The value at 0 mins represents mechanical properties after solution treatment and oil quenching. All data variations show a dramatic difference between the two temperatures and the trends are consistent between all three properties. After ageing at 480 °C, hardness, shear yield and ultimate shear strength values peak around one hour and remain steady thereafter. However, at the higher ageing temperature of 590 °C, a sharp peak is observed after 10 minutes followed by a sharp drop.

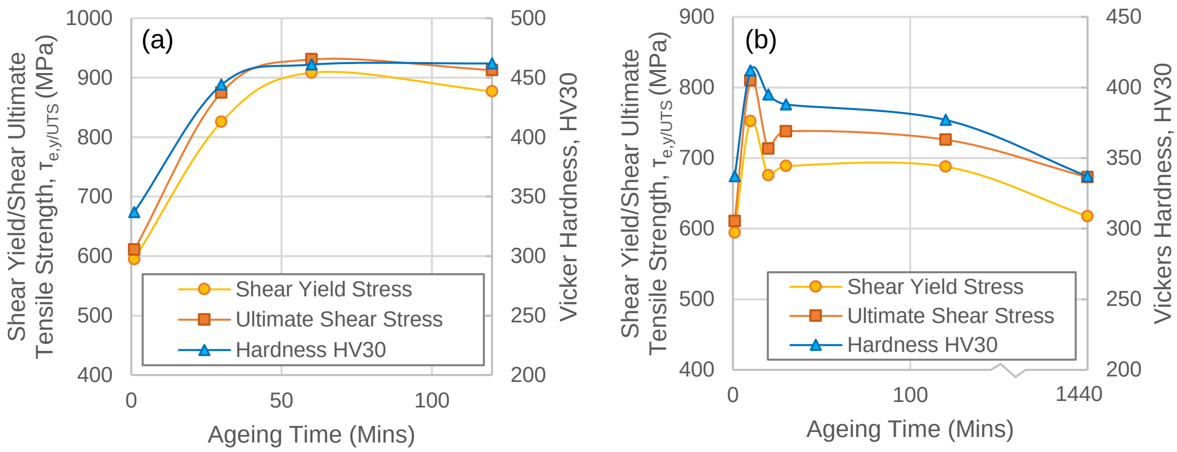

Figure 5. Change in shear yield and ultimate shear stress values determined by shear punch testing and hardness data determined by Vickers hardness [8] with ageing time at (a) 480 °C and (b) 590 °C.

In Figure 6, the correlation between shear properties and Vickers hardness values has been explored in; a linear relationship is shown to exist.

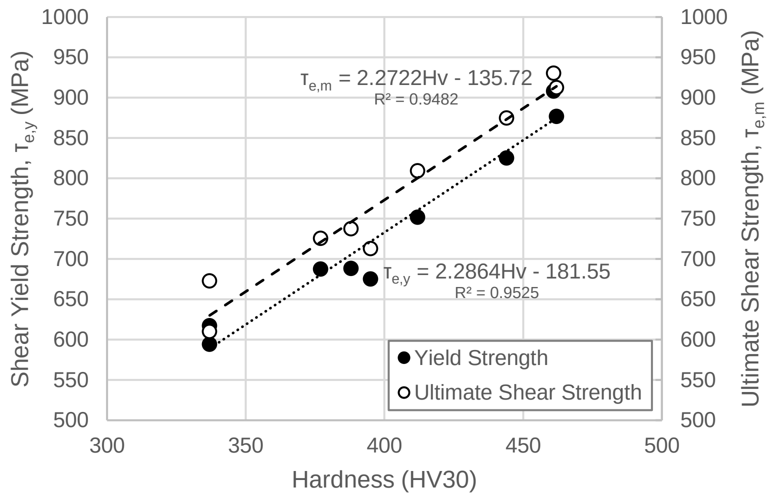

Figure 6. Relationship between Vickers hardness (HV30) and shear yield strength, $\tau_{e,y}$.

Using the correlations given in Equation 1 and Equation 2, values for yield and ultimate tensile strength have been determined from Vickers hardness measurements. The relationship between shear yield strength and tensile yield strength is given in Figure 7 and the relationship between ultimate shear strength and ultimate tensile strength is given in in Figure 8.

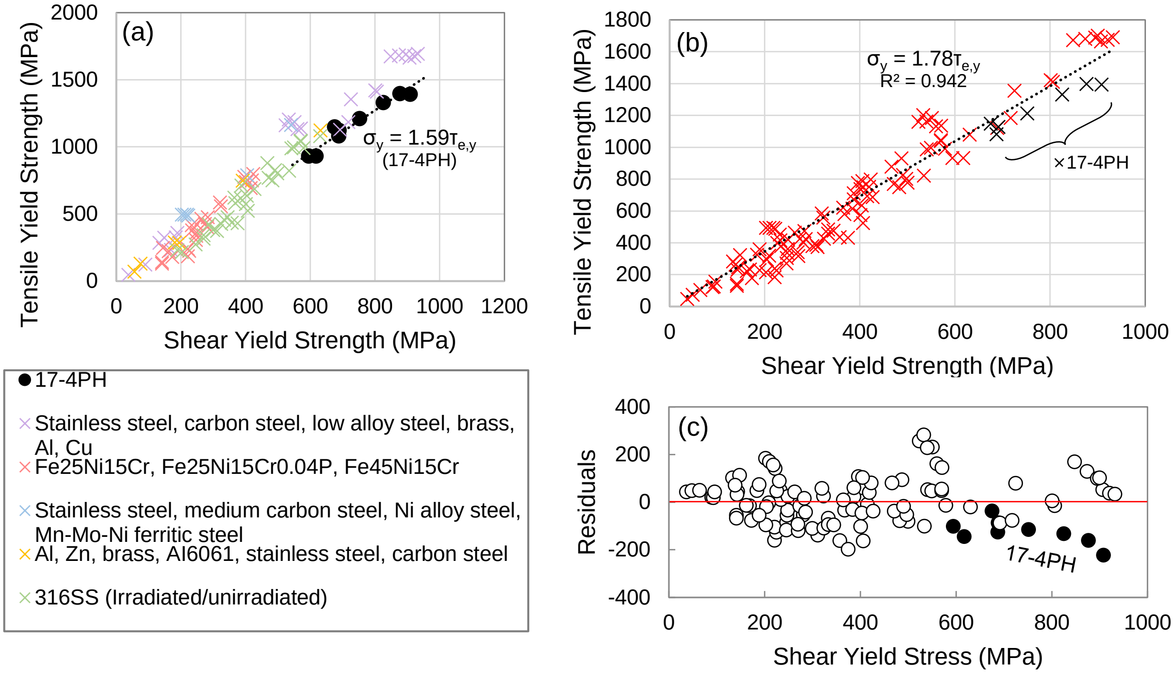

Figure 7. (a) Relationship between shear yield strength and tensile yield strength (determined from Vickers hardness data) for 17-4PH (correlation given on plot), alongside additional literature data for comparison. (b) Relationship between shear yield strength and tensile yield strength for combined data. (c) Residual plot to evaluate fit of correlation applied to combined data. Literature data obtained from [1] [2] [3] [5].

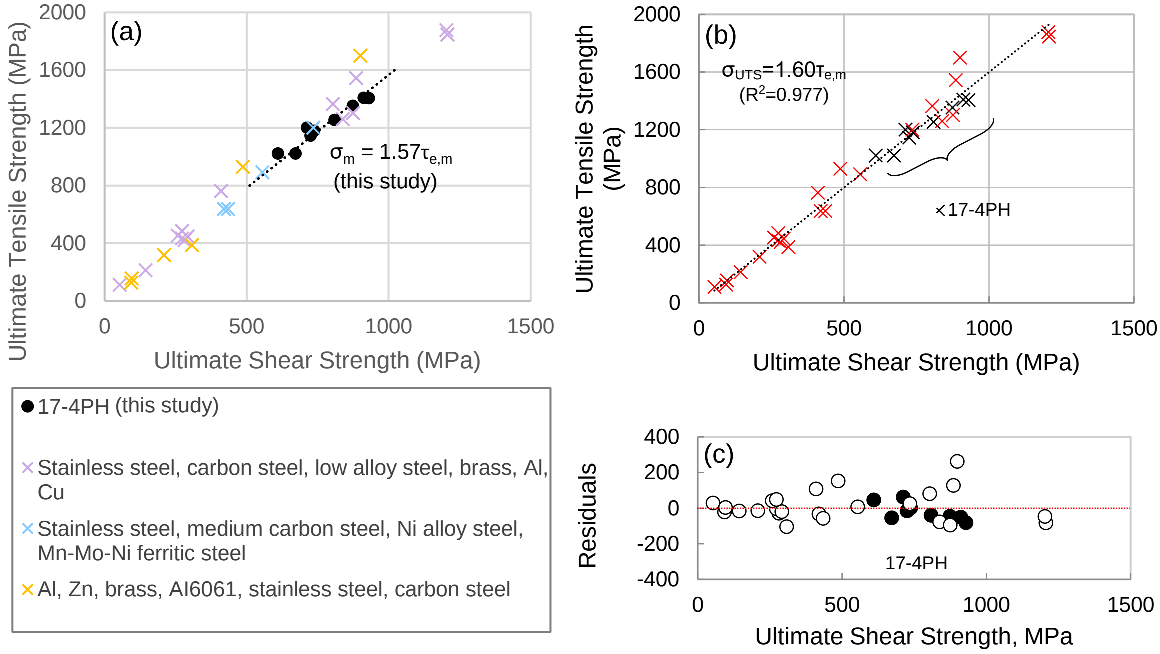

Figure 8. (a) Relationship between ultimate yield strength and ultimate tensile strength (determined from Vickers hardness data) for 17-4PH (correlation given on plot), alongside additional literature data for comparison. (b) Relationship between shear yield strength and tensile yield strength for combined data. (c) Residual plot to evaluate fit of correlation applied to combined data. Literature data obtained from [1] [3] [5].

In Figure 7a, the filled black data points show the correlation between shear yield strength and tensile yield strength and in Figure 8a the correlation between maximum shear strength and maximum tensile strength for heat treated 17-4PH. The ratios between tensile data and shear data, *m*, were found through linear regression. For the yield strength correlation, the value of the regression slope was 1.59 (r^2=0.95) with an x-axis offset, τ_0, of 0. For the maximum strength correlation, a regression slope value of 1.57 (r^2=0.91) was obtained, also with a τ_0 value of 0. These values of *m* are consistent, albeit slightly lower, than those reported in earlier work [1] [2] [3] [5] for a range of materials including stainless steel, carbon steel, Ni alloy steel, copper and brass. Linear correlations between shear and tensile data were shown in [1] [2] [3] [5], however *m* values ranging 1.63-2.15 for yield strength and 1.58-1.82 for maximum tensile strength were given. The relatively high correlation factors (R2) determined for these data indicate a fairly low-scatter linear fit.

Data from [1] [2] [3] [5] are also plotted on Figure 7a and Figure 8a and have been combined with data obtained for 17-4PH in this study to form a single correlation. A best fit line with an intercept through the origin (τ_0=0) was determined to be most appropriate and a correlation with an *m* value of 1.78 (r^2=0.95) for tensile strength and 1.60 (r^2=0.98) for maximum strength. The effectiveness of these correlations are investigated in Figure 7b-c and Figure 8b-c for yield strengths and maximum strengths, respectively. As shown in the residual scatterplots, the prediction of ultimate tensile properties from shear punch data can be determined with greater accuracy than the prediction of tensile yield properties using these single correlations. The difference in *plotted* yield data and *predicted* yield data is significantly greater than the difference in *plotted* maximum strength data and *predicted* maximum strength data; most plotted yield data sit within ±200 MPa of the regression equation line whereas, for the maximum strength data, most sit within ±100 MPa. This may reflect the difficulty in determining exact yield points in load-deflection curves. Shear yield stress values are determined using an offset criterion and are thus dependent on the slope of the curves which, themselves, can be affected by sample bending and stiffness of the test rig [11].

Theoretically, the von Mises yield criterion for a state of pure shear in isotopic materials gives the ratio of uniaxial to shear stress σ_y/τ_y as $\sqrt{3}$=1.73. An *m* value of 1.78 for the (combined data) yield strength correlation is slightly higher than the uniaxial to shear stress ratio using the von Mises criterion. Given the additional stresses that are likely to exist during shear punch testing, i.e. compression, stretching and bending in the clearance region between the flat-tipped punch head and receiving lower die, a value greater than $\sqrt{3}$ would not be unexpected.

Small Punch Test

Figure 9 compares the small punch test curves for the 17-4PH specimens in each condition. In the solution annealed condition, failure is associated with the formation of necking or local deformation, similar to that observed in tensile tests performed on ductile materials. However, the nature of failure changes with the application of a heat treatment and the production of a precipitation-hardened steel.

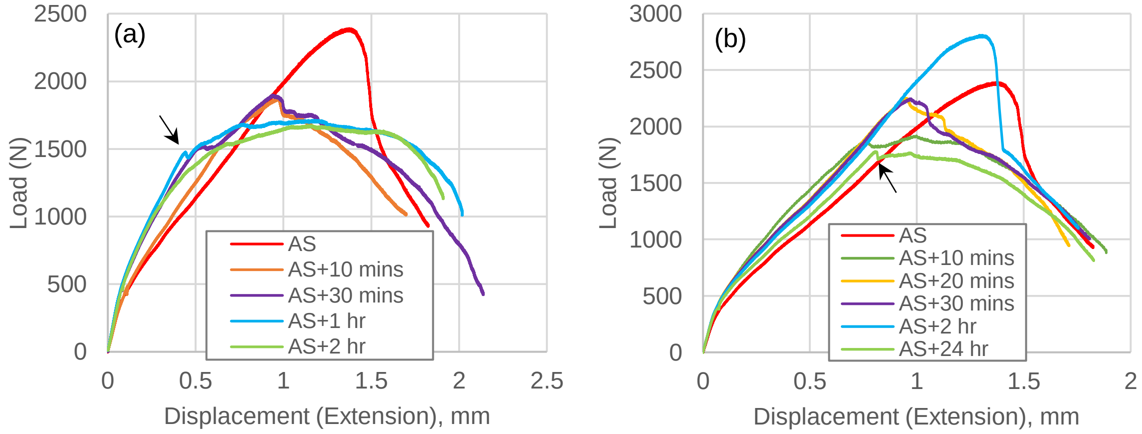

Figure 9. Small punch load-deflection curves for 17-4PH solution annealed at 1040 °C for 1 hr and heat treated at (a) 480 °C for times ranging 10 mins to 2 hr and (b) 590 °C for times ranging 10 mins to 24 hr.

In a number of tests, cracking occured prior to reaching maximum load. An example of this is shown in Figure 9a, indicated by an arrow on the load-deflection curve for the specimen heat-treated at 480 °C for one hour. In this case, after cracking the specimen was further deformed while still bearing increasing loads, but the general slope of the curve decreases. This indicates that the already initiated cracks are growing until total failure. Similar behaviour is shown in Figure 9b, again indicated by an arrow. However, in this case, no increase in load is shown after the first crack is initiated. With few exceptions, specimens in the as-received condition were the only ones to demonstrate a lack of pop-ins (sudden reductions in load) indicative of no cracks being initiated pior to the specimen reaching maximum load.

Given that early crack initiation within the plasticity regime is observed for most heat-treated specimens, using the well-adopted correlations for tensile stress estimation (Equation 6 and Equation 7) will likely yield limited meaningful information. Seeing as the ALT method correlates a force, P_i, at a lower displacement in the force-deflection curve than at P_{max}, it has been considered the more suitable relationship to estimate the uniaxial ultimate tensile strength from small punch test data.

In Figure 10, the variation in Vickers hardness, the load corresponding to the point of yield and the load determined at a displacement, v_i, of 0.645 mm as a function of holding time at 480 °C and 590 °C is given. Similar comparisons were made between hardness data and mechanical properties determined from shear punch testing. All data variations show a dramatic difference between the two temperatures and the trends are relatively consistent between all three properties.

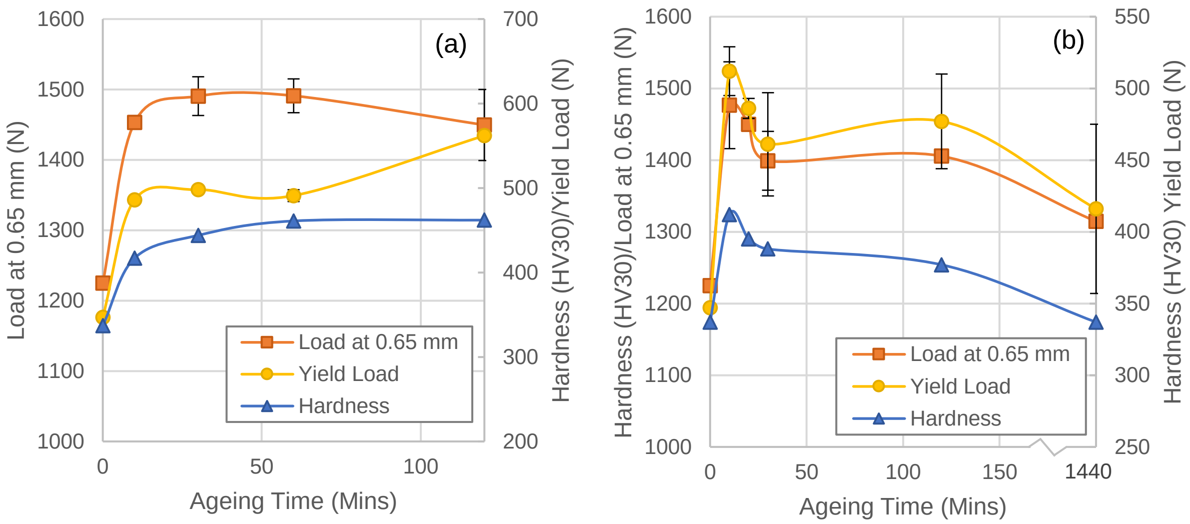

Figure 10. Change in small punch load taken at 0.65 mm, small punch load at the point of yield and hardness data determined by Vickers hardness [8] with ageing time at (a) 480 °C and (b) 590 ° C.

In Figure 11a, yield strength values that have been determined from hardness measurements have been correlated with P_y/t_0^2 to provide experimental values for the correlation factors α_1 and α_2 in Equation 5.

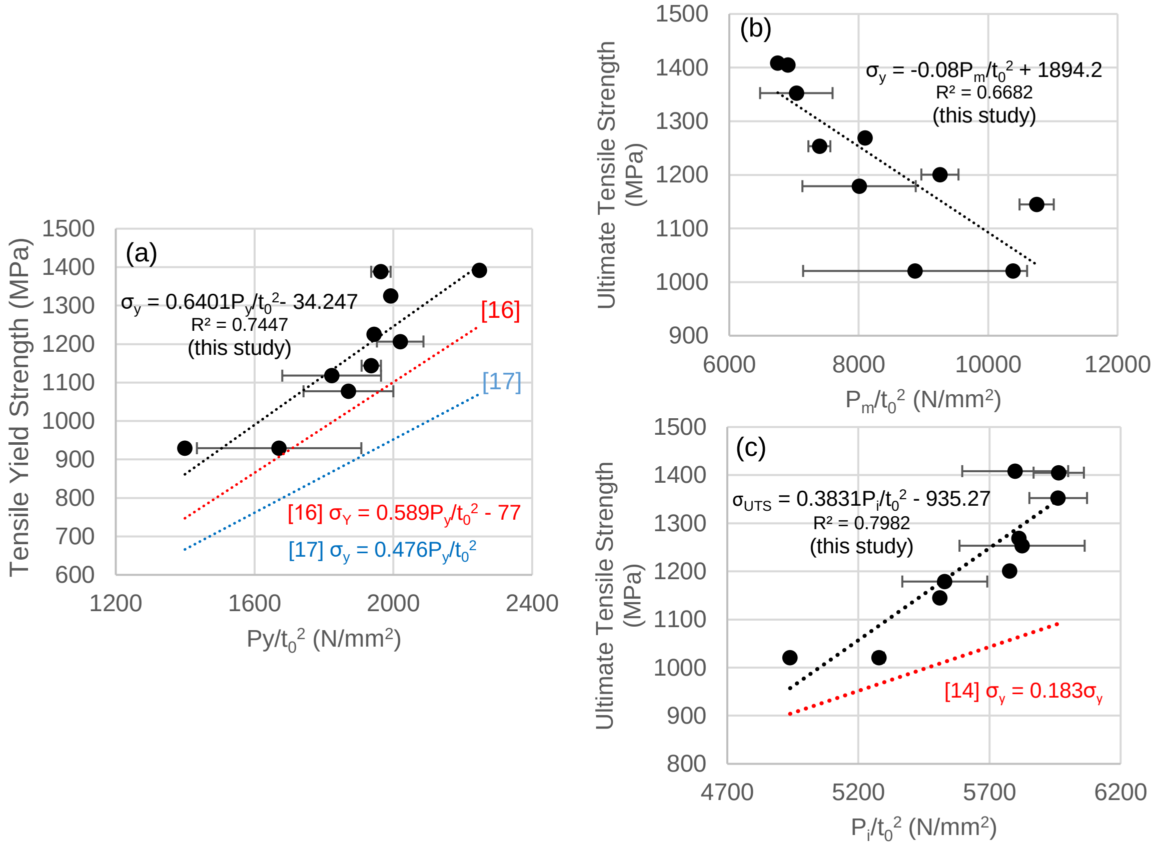

Figure 11. Correlations between (a) yield load (P_y/t_0^2) and tensile yield strength, (b) maximum load (P_m/t_0^2) and ultimate tensile strength and (c) load values taken at a displacement of 0.65 mm (P_i/t_0^2) and ultimate tensile strength. Literature data obtained from [14], [16] and [17] are also included in these plots.

Correlations obtained by Garcia et al. [16] for several steels including Eurofer, CrMoV and SS304 and Hurst and Matocha [17] for 14MoV6-3 steel have also been plotted in Figure 11a. All correlations showed a linear trend for the range of materials outlined, however the values of the regression coefficients and y-axis intercepts differ. This is likely associated with the range of materials investigated (differing strengths, microstructures and test temperatures); it is not possible to determine whether the differences in slope are due to a change in material property as the correlation for 17-4PH is dominated by rather large scatter in the data. These levels of scatter will also limit the accuracy of σ_y that can be determined from individual P_y measurements.

In Figure 11b, based on the relations given in Equation 6 and Equation 8, the ultimate tensile stress determined from hardness measurements has also been correlated with P_m/t_0^2 and P_i/t_0^2 from the small punch tests. This provides experimental values for the correlation factors β_2 (Equation 6) and β_{ALT} (Equation 8). Also shown in Figure 11b is the σ_{UTS}-P_i/t^2 correlation determined by Aldstadt et al. [14] [15] for a range of simulated steels with different tensile strengths and ductilities using a β_{ALT} value of 0.183. For all correlations, the coefficient of determination R^2 provides a quantitative measure of the goodness of the small punch based estimation of the yield and tensile stress. It is unsurprising that the scatter associated with the correlation in Figure 11b is significant, given that in the majority of cases, cracking initiatied well in advance of the maximum load (refer to Figure 9). This behaviour has also been discussed by Foulds et al. [18] who found that in the case of both ductile and brittle materials, crack initiation and (un)stable crack growth occurs prior to maximum load and thus neither Equation 6 or Equation 7 are appropriate for the estimation of tensile strength. As such, the correlation given in Figure 11b should not be considered meaningful. In Figure 11c, the force P_i is used instead of P_{max} and is correlated to ultimate tensile strength. As discussed by Altstadt et al. [14], this force can be associated with the onset of plastic instability and is therefore considered more suitable for a correlation with ultimate tensile stress. Some of the scatter shown in Figure 11c is a result of specimen fracture at a displacement $v<v_i$ (where v_i=0.645 mm), observed during several

tests on the 480 °C annealed material. In these cases, a value of 0.645 mm for v_i is not appropriate and the F_i based correlation would thus be considered invalid.

Comparing the relationship determined in this study for 17-4PH to that given in [14], differences in both the regression coefficient and y-axis intercept (Altstadt et al. [14] forces the intercept through zero) are given. Similarly to that discussed above, it is likely that these differences could be an effect of the different materials being investigated but is difficult to confirm given the scatter in the data.

Small punch versus shear punch testing

The similarity in test curves obtained during small punch and conventional uniaxial tensile testing has sparked interest for correlating the mechanical properties obtained by these two test types. The triaxial, time-dependent stress state in a small punch specimen, and the sensitivity of the test geometry, does make this non-trivial, however, significant effort has been, and is being, put into deriving these correlations. One of the main challenges associated with the small punch test is the apparent differences in yield/tensile strength-$P_{y,max,i}$ correlations from material to material; this observation is highlighted in this study and is well noted in the literature where a range of correlations have been established. Although the production of standards is addressing a number of issues regarding data reproducibility and the ability to carry out cross-laboratory comparisons [11] [19], the issue remains that relating uniaxial and small punch test data relies on a number of material constants. When material availability is limited (as will often be the case for irradiated material and during the development of next generation alloys), existing uniaxial data will likely be scarce and identifying the most suitable material constants will be challenging. The testing of a precipitation-hardenening steel in this study has also highlighted issues associated with materials that demonstrate brittle failure. Although Altstadt et al. [14] have proposed a correlation between force, F_i (taken at a displacement value prior to reaching maximum load) and ultimate tensile stress, when applied to the data obtained here, a number of tests still remained invalid given their early fracture.

One of the benefits of using the shear punch test is that the deformation and failure processes that occur during testing are analogous to those that occur in conventional uniaxial shear tests; load-displacement data can be interpreted in terms of uniaxial mechanical property data. The relationships between effective shear stress, $\tau_{y,m}$, and yield or maximum load in the shear punch test, $P_{y,m}$, do not rely on any material constant but instead take into account several shear punch test set-up parameters, including punch radius and specimen thickness. Effective shear yield and ultimate shear strengths obtained from shear punch testing can subsequently be related to ultimate tensile and yield properties and, although still reliant on material constants, this study has demonstrated that a meaningful single correlation can be formed; in addition to 17-4PH, data obtained from the literature for a range of materials, with a range of strengths, were considered. The assignment of a single, non-material specific, correlation to provide estimates of uniaxial tensile properties when uniaxial data is unavailable is extremely valuable and highlights the potential of shear punch testing.

Conclusions

The frequent limited amounts of material available to sample in-service reactor components non-invasively means the development of small specimen test techniques to accurately evaluate mechanical properties is highly important. This work has examined the suitability of determining yield and tensile strength properties of a precipitation-hardened stainless steel using shear punch testing and tensile data obtained from Vickers hardness testing.

Linear relationships between shear data and tensile data have been identified and regression coefficients have been determined that are consistent with those given in the literature. No x-axis offsets, τ_0, were found to exist for either correlation. When combined with literature data, single linear correlations between tensile data and tensile shear data have been identified for a wide range of material strengths that were not dissimilar to those correlations obtained for 17-4PH alone. Although both correlations had scatter, the level associated with the tensile yield strength-shear yield strength correlation was greater than that associated with ultimate strengths.

It has been demonstrated in [2] that a relationship exists between material strength and degree of scatter, whereby the scatter is greatest for lower strength materials. No such relationship was obvious in these data. It is, however, likely that the confidence in these correlations would be increased, the difference in plotted and predicted values reduced, and any trends associated with material strength would be more easily extracted, if multiple specimens were tested for each material condition. Ultimately, these correlations will allow tensile strengths to be determined from shear strengths using shear punch test data obtained from very small amounts of material.

Linear relationships have been established between small punch and uniaxial tensile data. However, material constants inconsistent with those given in the literature have been determined. This statement is particularly applicable to the relationship between ultimate tensile strength and the maximum load obtained in a small punch test. Although it has been previously shown that a relationship exist between these two parameters, the brittle nature and early fracture of 17-4PH small punch specimens prior to reaching maximum load, means limited meaningful information can be obtained for this material. To address these issues, an alternative correlation relating tensile strength to a load taken at a point prior to reaching maximum load was adopted; a correlation more consistent to that given in the literature was defined and the differences have been assumed a likely effect of the different materials being investigated and the level of scatter in the data.

These data suggest that, if uniaxial data is unavailable, as will often be the case when investigating irradiated or new generation materials, the shear punch test will provide more meaningful information than the small punch test. This will likely be more prevalent in embrittled materials.

Acknowlegdements

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