THE DEVELOPMENT OF A TENSILE-SHEAR PUNCH CORRELATION FOR YIELD PROPERTIES OF MODEL AUSTENITIC ALLOYS – G.L.Hankin, (I.P.T.M.E, Loughborough University, UK), M.L.Hamilton, F.A.Garner (Pacific National Northwest Laboratory)* and R.G.Faulkner (I.P.T.M.E, Loughborough University, UK)

OBJECTIVE

To refine an existing tensile-shear punch correlation using a large data base from three neutron-irradiated model austenitic alloys and to provide fundamental support for the empirical correlation.

SUMMARY

The effective shear yield and maximum strengths of a set of neutron-irradiated, isotopically tailored austenitic alloys were evaluated using the shear punch test. The dependence on composition and neutron dose showed the same trends as were observed in the corresponding miniature tensile specimen study conducted earlier [1]. A single tensile-shear punch correlation was developed for the three alloys in which the maximum shear stress or Tresca criterion was successfully applied to predict the slope. The correlation will predict the tensile yield strength of the three different austenitic alloys tested to within ±53 MPa. The accuracy of the correlation improves with increasing material strength, to within ±43 MPa for predicting tensile yield strengths in the range of 400 - 800 MPa.

PROGRESS AND STATUS

Introduction

A number of experiments have been done recently [2-5] to facilitate development of a tensile-shear punch correlation, i.e., a relationship between uniaxial tensile strength and effective shear strength that would allow the use of shear punch data to predict tensile data. In order to validate the proposed tensile-shear punch correlation it is desirable to test a variety of materials exhibiting a wide range of microstructures and mechanical properties. The ^{59}Ni isotopic tailoring experiment [6], originally designed to elucidate the effect of fusion-relevant amounts of helium on austenitic structures, produced such a specimen matrix. The experiment used an isotopic tailoring approach to evaluate the effect of helium generation rates typical of a fusion reactor environment on the tensile properties of three neutron-irradiated model austenitic alloys (Fe-25Ni-15Cr, Fe-25Ni-15Cr-0.04P and Fe-45Ni-15Cr). Helium generation rates relevant to a fusion reactor were produced by an (n,α) reaction involving the decay of ^{59}Ni, an isotope which is not found in natural nickel. Nickel enriched in the ^{59}Ni isotope was extracted from Inconel 600 fracture toughness specimens, which were originally irradiated in the Engineering Test Reactor (ETR). The enriched nickel contained 2% of the ^{59}Ni isotope. The helium to dpa (displacements per atom) ratios obtained were of the order of 0.5 appm He/dpa for the undoped alloys and up to 20 appm He/dpa for the ^{59}Ni-doped alloys.

Transmission electron microscope (TEM) disks of the three Fe-Ni-Cr alloys were irradiated side-by-side with the miniature tensile specimens as part of the ^{59}Ni experiment in the Fast Flux Test Facility's Materials Open Test Assembly (FFTF-MOTA). Each alloy was

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irradiated both with and without ^{59}Ni content, and were prepared in both the cold worked (CW) and solution annealed (SA) conditions. The twelve alloy combinations were irradiated at three different temperatures and were available from up to four discharges of the FFTF-MOTA. The TEM discs were originally intended for TEM examination only but many of them were never used since 3 to 6 specimens were available at each set of irradiation conditions. The remaining TEM discs were therefore available to generate effective shear strength data, which when coupled with the original tensile data, resulted in a large database for further refining the existing tensile-shear punch correlation.

Experimental Procedure

The shear punch test is essentially a blanking operation in which a 1 mm diameter punch is driven at a constant rate of 0.127 mm/min. (0.005 in./min.) through a TEM-sized disk (nominally 0.25 mm thick and 2.8 mm in diameter). The disk is constrained along both its upper and lower surfaces in a test fixture, which also guides the punch. The load on the punch is measured as a function of specimen displacement, which is taken to be equivalent to the crosshead displacement [3]. The yield and maximum loads are taken from a plot of punch load versus punch displacement. Effective shear yield strength (τ_{sy}) and maximum shear strength (τ_{sm}) are evaluated from these values, respectively, by the following equation [4]:

$$\tau_{sy,sm} = \frac{P}{(2\pi rt)} \qquad (1)$$

where P is the appropriate load, r is the average of the bore and punch radii, and t is the specimen thickness. An earlier report [7] provides more details of the shear punch test and the facility in which the irradiated materials were tested.

Previous work has shown that shear yield and maximum strengths obtained by shear punch test methods can be correlated to tensile yield and ultimate properties. When corresponding sets of τ and σ are plotted they fall along a straight line. A linear regression is performed to obtain the constants m and K in:

$$\sigma = m\tau + K \qquad (2)$$

The y-axis intercept, K, was originally ascribed to punch-die-specimen friction [8] and the regression slope previously appeared to be somewhat material-dependent [4]. For the purpose of this study, equation (3) will be used, in which $\tau_0 = -K/m$ from equation (2).

$$\sigma = m(\tau_{meas} - \tau_0) \qquad (3)$$

The offset parameter τ_0 (the x-axis intercept of the regression line) is used to indicate that the offset is some frictional characteristic which is associated with the shear punch test and not the tensile test.

Two TEM specimens were available for each irradiated condition and five specimens for each unirradiated starting state. The shear punch data were first evaluated for consistency with the corresponding tensile data [1]. The tensile shear-punch database was then used to refine the existing correlation coefficients.

Results

From the results of shear punch tests on the unirradiated material it was established that the effective shear yield and maximum strengths of duplicate specimens typically exhibited a scatter of ±15 MPa. Figure 1 shows the variation of effective shear yield strengths of each of the alloys with increasing dpa for specimens irradiated at 365 and 490°C. As expected, the results of the shear punch test were in good agreement with those from the original miniature tensile specimen study [1]. It can be seen that helium/dpa ratios typical of a fusion reactor environment (~15-20 appm He/dpa) have no significant effect on the yield properties of the materials when compared to the scatter in the data from their respective

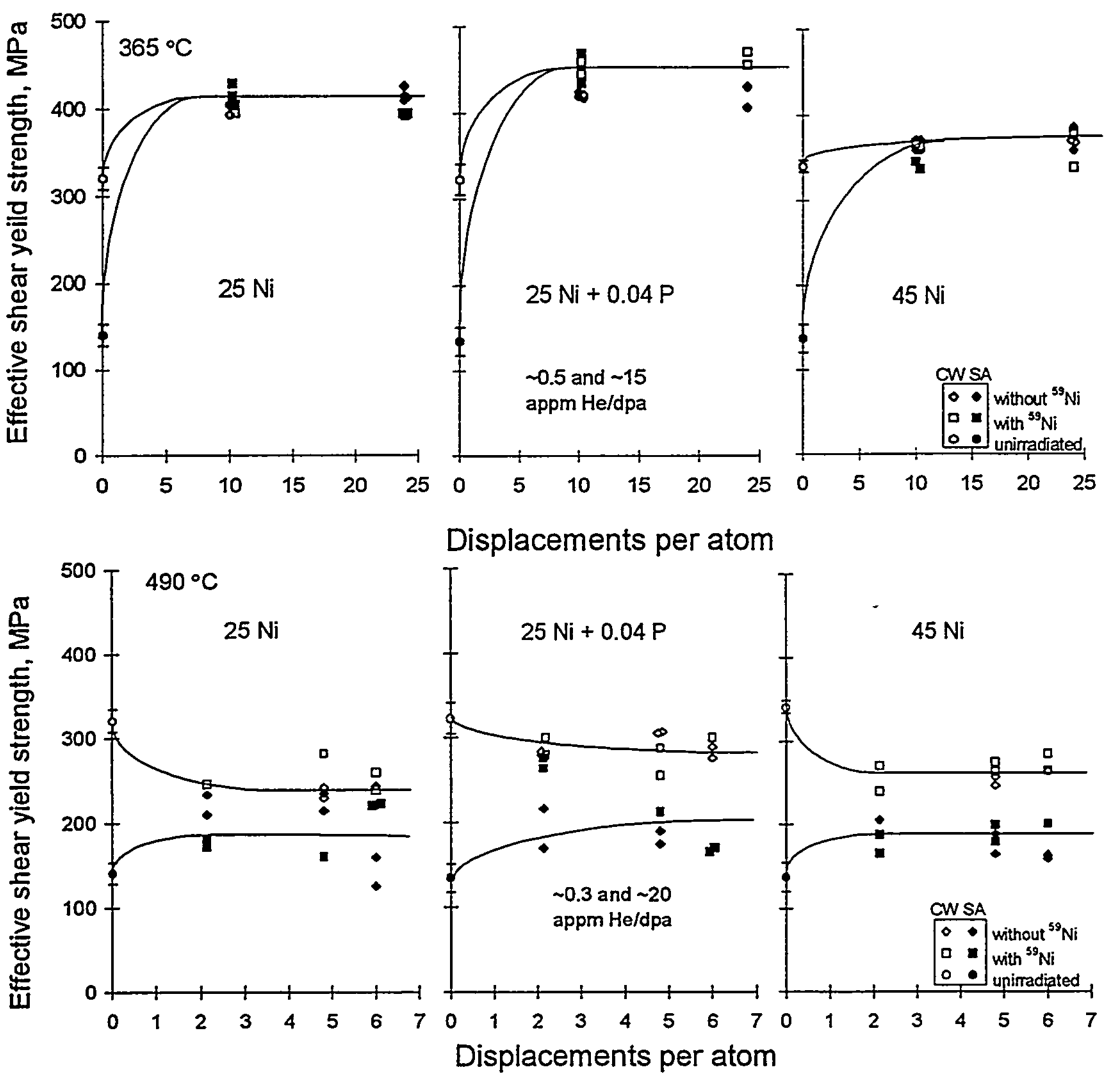

Figure 1. The influence of thermomechanical starting state and different He/dpa ratios on the effective shear yield strength of three austenitic alloys irradiated below core at 365°C and above core at 490°C. The average helium generation rates for undoped and doped specimens are shown on each figure.

controls. The value of τ_{sy} of each of the irradiated materials approaches a saturation level that is dependent on the irradiation temperature, but independent of the thermomechanical starting state. Convergence in material strength with increasing dpa is very clear for the material irradiated at 365°C (Fig.1), but has not been completed at 490°C due to the low dpa levels achieved.

The tensile-shear punch relationship was first produced for the yield properties of the three materials individually. A linear regression on each data set yielded slopes that were ~2 (Table 1). On the basis of the maximum shear stress or Tresca yield criterion, the slope was fixed at 2 (Fig. 2). Each correlation was then adjusted by the appropriate offset parameter, τ_0, and all three were combined to form a single correlation (Fig. 3). A practical measure of the accuracy of the final correlation was calculated as the standard deviation of σ_y (±53 MPa). Thus in practice, it would be expected that shear punch yield data would be used to predict tensile yield strength to within 53 MPa, or to within 43 MPa for σ_y between 400 and 800 MPa (Fig. 4).

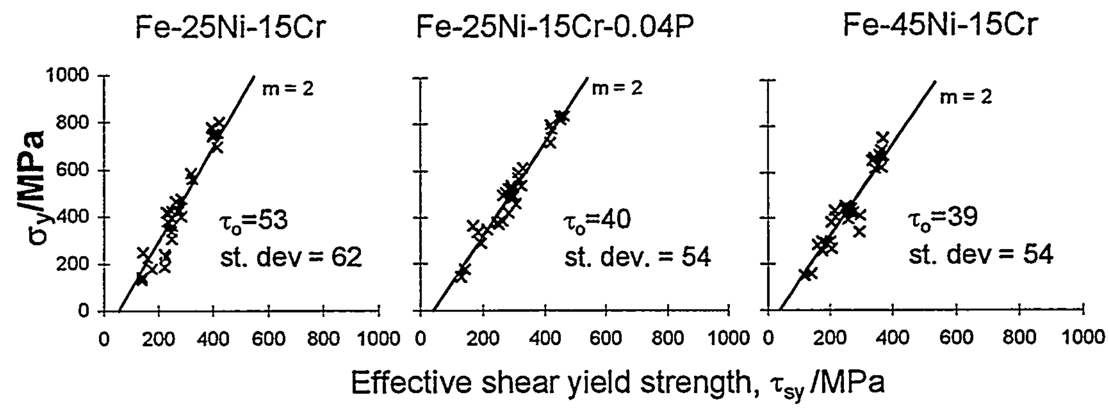

Figure 2. Tensile-shear punch correlation for three austenitic alloys with regression slopes defined as 2 by the Tresca criterion.

<u>Discussion</u>

It was noted that when the regression was applied to the three austenitics individually, the slopes were all ~2 (Table 1). Earlier work summarised by Hamilton [4] shows the value of the slope to be somewhat variable for individual material systems using smaller data sets. For example stainless steels appear to have a slope of ~1.7 and values of 2.8 and 2.6 were seen for vanadium and aluminium respectively. When the austenitic material data sets were adjusted for τ_0 and combined, the slope of the final regression was almost exactly equal to 2. The wide range of material strength data available in the current study was considered to increase the confidence in the accuracy of the correlation and so the question arose whether there was some fundamental reason for the regression slopes to tend to this value. The ratio of shear to uniaxial stress in the maximum shear stress or Tresca yield criterion is 2, i.e.,

$$\sigma_y = 2\tau_{\max} \tag{4}$$

This result would only be expected if a state of pure shear can be assumed in the process zone of the specimen during a shear punch test. This is not necessarily the case since there is a small clearance (~0.02 mm) between the punch and die, which would lead to other stress components being present in the TEM specimen under test.

Table 1. Regression constants for tensile-shear punch correlation of three austenitic alloys.

Material	Linear regression of yield data		Tresca criterion applied to yield data (slope of 2)	
	m (slope)	τ_0	*m* (slope)	τ_0
Fe-25Ni-15Cr	2.3	84	2.0	53
Fe-25Ni-15Cr-0.04P	2.0	38	2.0	40
Fe-45Ni-15Cr	2.1	49	2.0	39

Kullen [9], however, previously applied the Tresca yield criterion with some success to predict the tensile yield strengths of a number of materials after conducting a series of 3 mm punch tests to produce TEM discs. Lucas [2] noted that the regression coefficient in a tensile-shear punch correlation for yield data from a variety of materials when combined was close to $\sqrt{3}$ = 1.73. This is the ratio of shear to uniaxial stress in the von Mises yield criterion. Attempts at fitting the current data to the von Mises criterion were unsuccessful. The individual material regressions were calculated for a slope of 2 (Fig. 2) to investigate the suitability of applying the Tresca criterion. The resulting values of τ_0 are displayed along side those for the individual data sets in Table 1. It can be seen that the values of τ_0 appear to be converging, which indicates that a single value may be assigned to this alloy class. The three correlation were adjusted by their respective values of τ_0 and combined to form a single correlation (Fig. 3).

The effectiveness of the correlation is measured by the standard deviation of the measured tensile data from the value that the correlation predicts from the shear punch yield strength. It can be seen from Figure 3 that the majority of the data lie within ± 53 MPa (a 68% confidence limit). It is likely that if multiple shear punch tests could be carried out for a particular material

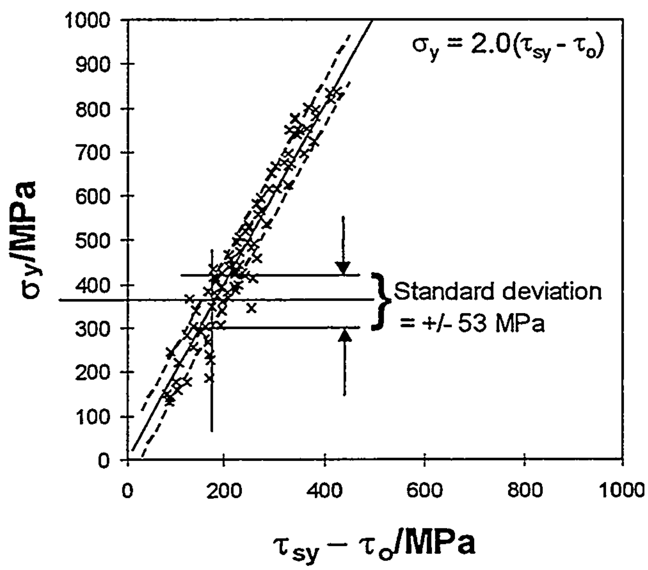

Figure 3. Single correlation developed from all three austenitic alloys.

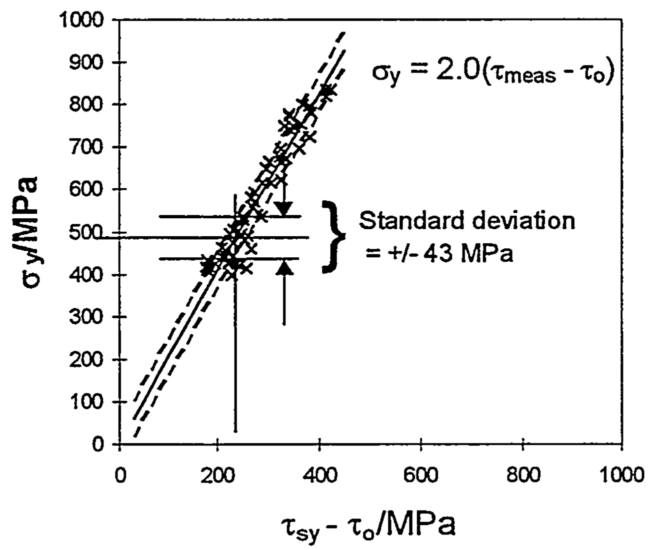

Figure 4. Single correlation for all three austenitic alloys for σ_y > 400 MPa.

condition, the standard deviation observed in the correlation would be reduced since the average of data from only two shear punch tests and one or two miniature tensile test were used for each correlation point. The difficulty of defining a common practice for determining the yield point for a shear punch test also contributes to the prediction accuracy. The 2% strain offset used to determine the tensile yield strength cannot be applied to the shear punch test. It is therefore difficult, especially for softer materials, to extract effective shear yield strength data. This is evident in Figure 3 where the scatter is clearly greatest for the data from the lower strength materials. It was for this reason that Figure 4 was constructed for only those materials having a measured tensile yield strength greater than 400 MPa, where the standard deviation was reduced to ± 43 MPa.

CONCLUSIONS

The shear punch test will reliably replicate the trends obtained in tensile test data. This is an important result since tensile specimens are not always available. A reliable correlation has been developed which can be used to predict yield properties over a wide range of material strengths to an acceptable level of accuracy. Applying the Tresca criterion would appear to be valid, but further qualification of this theory is required. The Tresca criterion is superior to von Mises' for this data set. The offset parameter requires further investigation before definitive conclusions can be drawn as to its origin and nature.

FUTURE WORK

Similar analysis will be applied to the shear maximum strength data from this study. Additional testing on both TEM and miniature tensile specimens will be performed on a set of 316 austenitic stainless steel variations irradiated over a wide range of conditions in FFTF-MOTA and the validity of the correlation will be further assessed with these data.

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