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Validation of the shear punch–tensile correlation technique using irradiated materials

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Abstract

In previous studies on a variety of unirradiated materials, a linear relationship was developed between uniaxial tensile strength and effective shear strength, as determined from the shear punch test (SPT). Using the same data, a correlation was also developed to predict tensile uniform elongation from shear punch data. Validation of both correlations using a new database on both irradiated and unirradiated materials has been completed successfully.

1. Introduction

A number of shear punch experiments have been completed to assist the development of an empirical relationship between uniaxial tensile properties and data from the shear punch test (SPT). It has been demonstrated that tensile strength data can be linearly related to effective shear strength data obtained from SPTs on transmission electron microscopy (TEM) disks for a variety of unirradiated alloys exhibiting yield strengths that ranged from 100 to 800 MPa [1–4]. In the investigation by Lucas and coworkers [1], a ductility correlation was also developed that linearly related tensile uniform elongation to effective shear strength data. Toloczko and coworkers [5] further developed this relationship. With the exception of one set of irradiated aluminium alloys [3] and a second set of irradiated 316 stainless steel (SS) [6], shear punch testing has thus far only been carried out on unirradiated materials, and so it is necessary to extend the materials database to include highly irradiated materials.

The intent of the current work has been to demonstrate the usefulness of the SPT in evaluating mechanical properties of irradiated alloys so that tensile behaviour can be predicted when irradiated tensile specimens are unavailable or when the material might be too radioactive to test at larger sizes.

2. Experimental

2.1. Materials

SPTs were performed on two sets of irradiated specimens. In the first group, which is referred to as the ^{59}Ni doping series [7], TEM disks of three simple model alloys (Fe–25Ni–15Cr, Fe–25Ni–15Cr–0.04P, and Fe–45Ni–15Cr) were available. Each alloy was available in the solution annealed (1030°C for 30 min) and 20% cold worked (CW) starting condition, and was isothermally irradiated in the Fast Flux Test Facility Materials Open Test Assembly (FFTF-MOTA) through as many as four irradiation periods at temperatures ranging from 365°C to 495°C. The total dose accumulated for each specimen ranged from 2.1 to 52 displacements per atom (dpa) and unirradiated control specimens were also available. The corresponding tensile data had been previously generated from tensile specimens irradiated side-by-side with the TEM disks [8].

In the second group, three variants of a 20% CW 316 SS, which had slightly different levels of minor alloying elements (C, P, Ti and Si), were irradiated through three

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discharges in FFTF at 5 temperatures between 400°C and 730°C to doses ranging from 12 to 88 dpa. These specimens were in the form of both TEM disks and miniature tensile specimens, which were irradiated side-by-side. Unirradiated control specimens were also available. In addition, another set of unirradiated 316 SS TEM disks and matching miniature tensile specimens at four CW levels between 0% and 75% were available for testing.

Two TEM specimens were tested for each irradiated condition and five specimens for each unirradiated condition for both the ^{59}Ni doping series and the 316 SS variations. The tensile testing for the ^{59}Ni alloys was completed in a previous study [8], and two miniature tensile specimens were available for each irradiated condition for the 316 SS variations. At least three shear punch tests and three tensile tests were completed for the unirradiated CW 316 SS alloy conditions. 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 standard deviation of ~15 and ~8 MPa, respectively. The trends seen in the mechanical properties of the ^{59}Ni tensile and shear punch specimens as a function of dose and irradiation temperature are presented in a companion paper [9].

2.2. Shear Punch Test

The shear punch test (SPT) 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 [1]. 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]

$$\tau_{\mathrm{sy,sm}} = \frac{P_{\mathrm{sy,sm}}}{(2\pi r t)}, \tag{1}$$

where $P_{\mathrm{sy,\,sm}}$ is the appropriate load, r is the average of the bore and punch radii, and t is the specimen thickness.

2.3. Shear punch–tensile strength correlation

Previous work has shown that shear yield and maximum strengths obtained by SPT 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 τ_0

$$\sigma_{\mathrm{y,UTS}} = m(\tau_{\mathrm{sy,sm}} - \tau_0) \tag{2}$$

The x-axis intercept, τ_0, is referred to as the offset parameter and is associated with the SPT and not the tensile test. τ_0 was originally ascribed to punch-die-specimen friction [10] and m and τ_0 appeared to be somewhat material-dependent [4]. In these studies, it was shown that different alloy sets could be combined to form a single correlation by choosing an appropriate value of τ_0 for each alloy set.

2.4. Shear punch–tensile ductility correlation

Tensile uniform elongation has also been predicted from shear punch properties [1,5]. Toloczko et al. [5] showed that a linear correlation existed between tensile uniform elongation and shear punch properties for a variety of unirradiated alloys. The first step in the development showed that a linear relationship existed between measured tensile strain-hardening exponent, n, (from tensile test data) and a strain-hardening exponent, n_σ, predicted from the ratio of ultimate tensile stress to tensile yield stress, $\sigma_{\mathrm{m}}/\sigma_{\mathrm{y}}$

$$\left(\frac{n_\sigma}{0.002}\right)^{n_\sigma} = \frac{\sigma_m}{\sigma_{\mathrm{y}}}. \tag{3}$$

Eq. (3) was derived by Lucas et al. [1] from the definition of power law strain hardening ($\sigma = \mathrm{K}\varepsilon_{\mathrm{pl}}^{n}$) at yield and maximum strength, where the true plastic strain $\varepsilon_{\mathrm{pl}}$ equals 0.002 at yield, and ε_{u} equals n at the onset of necking or maximum strength. The measured strain-hardening exponent, n, was determined from the slope of σ vs. $\varepsilon_{\mathrm{pl}}$ traces on log–log plots. Analysis of the tensile tests verified that $\varepsilon_{\mathrm{u}} \approx n$ for the materials tested.

In the next step, $\sigma_{\mathrm{m}}/\sigma_{\mathrm{y}}$ in Eq. (3) was replaced with the corresponding ratio of effective shear maximum stress to effective shear yield stress ($\tau_{\mathrm{sm}}/\tau_{\mathrm{sy}}$), resulting in n_τ, analogous to n_σ. A plot of n vs. n_τ was then constructed. When considering that σ_{m} and σ_{y} represent true stresses and τ_{sm} and τ_{sy} are more like engineering stresses, this step was quite an approximation, but nevertheless a linear relationship was also found to exist between n and n_τ with a slope similar to that of the n vs. n_σ correlation. The linear nature of these relationships makes it possible to obtain finally a linear relationship between true uniform tensile elongation and n_τ.

3. Results and discussion

3.1. Shear punch–tensile correlation

Fig. 1 shows the correlation between effective shear yield strength and uniaxial tensile yield strength for the three model alloys from the ^{59}Ni doping experiment. In all cases, the slopes were ~2. Earlier work summarised by Hamilton et al. [4] on a variety Fe, Cu, V and Al based alloys, showed the slope to be somewhat variable when regressions were performed for individual alloys. For example, SS appeared to have a slope of ~1.7 whereas values of 2.8 and 2.6 were seen for vanadium and aluminium alloys respectively. However, Hamilton et al. [4] showed that the alloy sets, which generally had small strength ranges, could be combined to form a single correlation by choosing an appropriate value of τ_0, i.e., the values of τ_0 were chosen to obtain the best fit to a line with an intercept through the origin. When this approach was applied to the ^{59}Ni alloys, a correlation with slope 2 was found. 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 as to whether there is some fundamental reason for the regression slopes to tend to this value.

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 uniaxial to shear stress in the von Mises yield criterion for a state of pure shear, i.e., $\sigma_y/\tau_y = \sqrt{3}$. The Tresca yield criteria, which amounts to a simplified and more conservative version of the von Mises yield criterion, gives a ratio of 2 if a state of pure shear is assumed for the SPT. Kullen [11] previously applied the Tresca result to predict the tensile yield strengths of a number of materials after conducting a series of 3 mm diameter punch tests on TEM disks. However, additional stresses that are likely to exist from stretching and bending in the clearance region between the punch and die should be considered in the application of either yield criterion. If these additional stresses are inserted into the von Mises yield criterion for the state of stress during the SPT, the ratio of uniaxial to shear will be greater than $\sqrt{3}$.

Recognising that there will be additional stresses present in the shear zone of the specimen in the SPT, and in an effort to derive a simple and consistent correlation between tensile yield and effective shear yield stresses for this work it was decided that all the data would be fit to a single master slope. As the value of the regression slopes for yield correlation in this work was on or about 2, this was the value chosen for the master slope. Regressions were recalculated for the three ^{59}Ni materials with the slope set equal to 2, producing a new τ_0 value for each alloy. The three ^{59}Ni data sets are combined on a plot of σ_y vs. $(\tau_{sy} - \tau_0)$ in Fig. 2. By this method, τ_0 has been determined in a more controlled manner than by the previous method of choosing the "best fit" value, and it can be seen that the data now fit a single correlation line.

The effectiveness of the correlation was measured by the standard deviation of the measured tensile strength from the value that the correlation predicts from the shear punch yield strength. It can be seen from Fig. 2 that the standard deviation of the predicted tensile value is 53 MPa. It is likely that the standard deviation observed in the correlation could be reduced since each plotted point represents only two SPT and one or two miniature tensile tests. The difficulty of defining a standard procedure for determining the yield point in a SPT also contributes to the prediction accuracy. It is difficult, especially for softer materials, to extract effective shear yield strength data. The scatter is clearly greatest for the data from the lower strength materials. For ^{59}Ni materials having a measured tensile yield strength greater than 400 MPa, the standard deviation was reduced to 43 MPa.

The shear punch–tensile correlation for the 316 variations is shown in Fig. 3. A number of alloys are

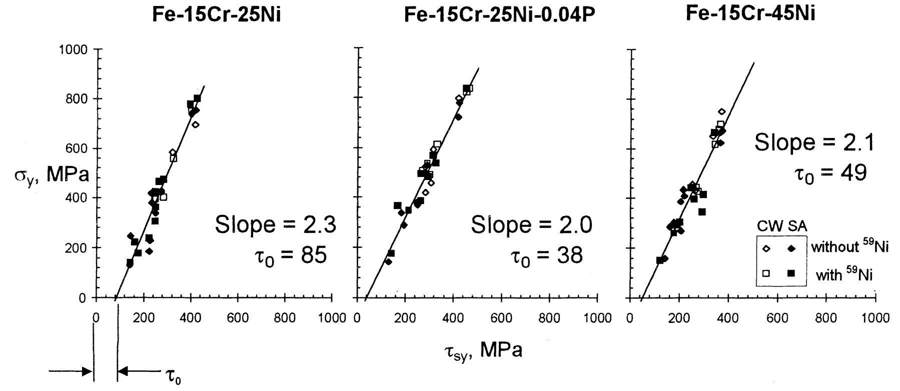

Fig. 1. Correlations between effective shear yield strength, from the SPT, and uniaxial tensile yield strength from miniature tensile specimen testing for three model austenitic alloys from the ^{59}Ni experiment. The data have not been adjusted for fixed slope or τ_0 offset.

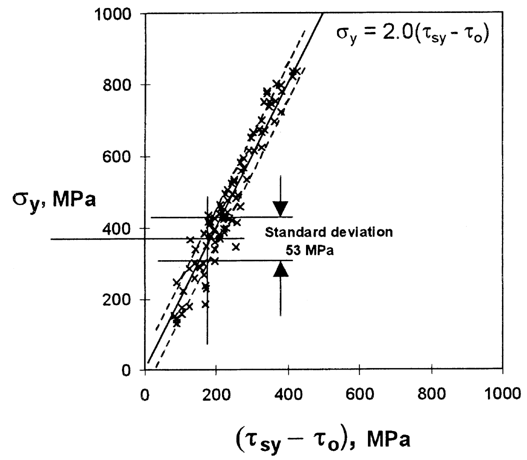

Fig. 2. Correlation between σ_y and $(\tau_{sy} - \tau_0)$ for three model austenitic alloys from the ^{59}Ni series. The τ_0 value for each material was determined after setting a slope of 2 to each data set in a correlation of σ_y and τ_{sy}.

included in the same correlation since there was less variation in alloy composition than in the case of the ^{59}Ni alloys. The graph shows two regression lines. The first, with slope 2.2 and $\tau_0 = 117$ MPa, is the actual regression line for the data shown and the second line has a fixed slope of 2 with a corresponding value of $\tau_0 = 88$. The second line was added to investigate the application of the same slope used in the ^{59}Ni series correlation. It can be seen that if more data were available for softer materials, the line may have been pivoted towards a slope of 2. The offset parameter is slightly larger than was seen for the ^{59}Ni alloys, which enforces conclusions by previous authors that this value is material dependent [4,10]. The same slope and offset parameter can be defined for the unirradiated materials as for the irradiated materials. The standard deviations of the measured tensile data from the correlation predictions for the true and forced-slope regression lines are 57 and 62 MPa, respectively, which is slightly larger than was previously seen in the ^{59}Ni correlation.

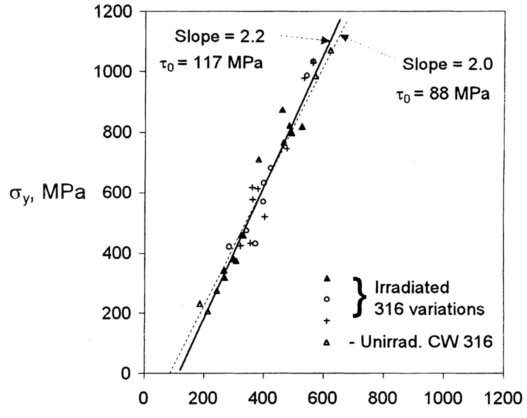

Fig. 3. Correlation between τ_{sy} and σ_y for three irradiated 316 SS variations and an unirradiated set of 316 SS with various CW levels. The solid line represents a regression on all the data and the dashed line shows a line of slope 2 for comparison.

The correlation between ultimate tensile strength and effective shear maximum strength generally shows larger τ_0 values and slopes comparable to the yield correlation. This is consistent with the findings of previous authors. No explanation is offered as to the origin of the offset, but as in the case of the yield strength correlation, τ_0 appears to be material dependent. The shear punch–tensile correlation for the maximum strength condition for the ^{59}Ni series has an unadjusted slope of 2.0 and offset value of 135 MPa, while the unadjusted 316 series has a slope of 1.8 and an offset value of 170 MPa. A previous correlation on unirradiated SS gave a slope of 2.2 and a τ_0 offset of 212 MPa [4].

A more in-depth knowledge of the exact stress state within the TEM disk during the punching operation may offer insight into the origin of the slope and offset in the tensile yield-effective shear yield correlation. Such insight could be obtained using finite element analysis, which is now in progress.

3.2. Ductility correlation

Fig. 4(a)–(d) show the various stages in the development of the ductility correlation described earlier for the ^{59}Ni series alloys. Fig. 4(a) shows a tight linear relationship between the measured tensile strain hardening component, n, and n_σ, predicted from Eq. (3). In Fig. 4(b), the value of n_τ was obtained by exchanging σ_m/σ_y with τ_{sm}/τ_{sy} in Eq. (3). A linear relationship with a similar slope to that seen in the n vs. n_σ comparison was obtained. The lack of one-to-one behaviour seen in both the n vs. n_σ and n vs. n_τ plots is due to the method for estimating n_σ or n_τ, and not due to any factor peculiar to the SPT.

Fig. 4(c) shows a linear relationship between n and true tensile uniform elongation that provides the link between n_τ and true uniform elongation, shown in Fig. 4(d). The significance of this is that tensile elongation data can now be estimated from effective shear yield and shear maximum stresses from the SPT.

Fig. 5(a) shows a plot of true uniform elongation versus n_τ for the irradiated 316 variations and unirradiated 316 SS. The data for the 316 material variations show less scatter than the equivalent plot for the ^{59}Ni alloys. This may be a reflection of the quality of specimens available, and the number of tested specimens contributing to each data point, i.e., there was greater

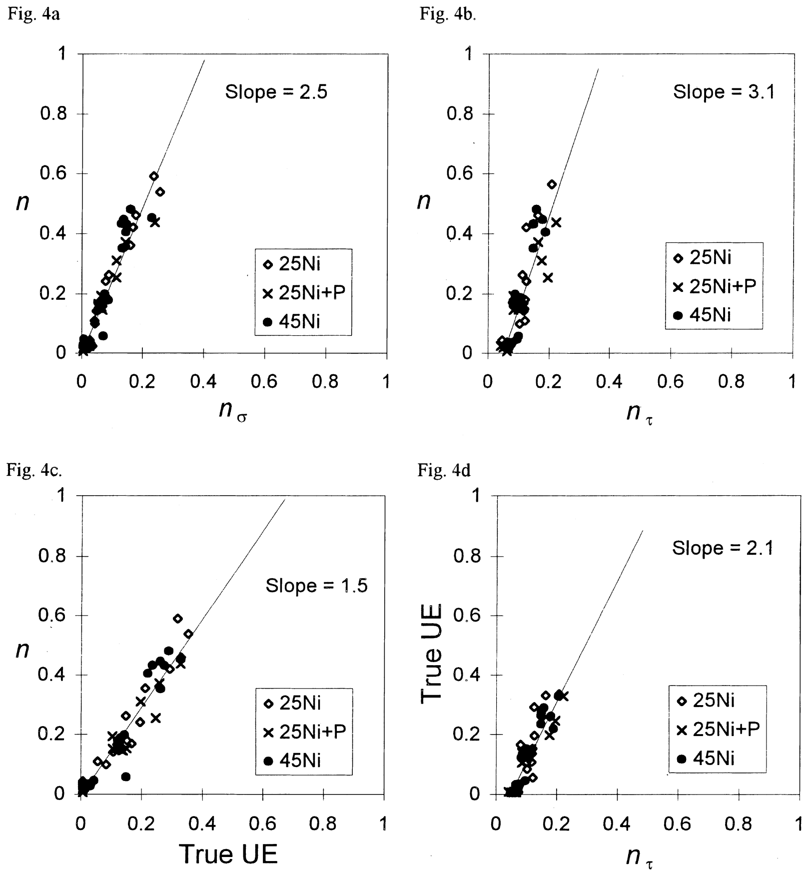

Fig. 4. (a)–(d) Development of a ductility correlation that shows a linear relationship between tensile true uniform elongation and SPT results.

redundancy in the 316 SS specimen matrix. The result may also reflect refinements in the practices employed during shear punch testing, in particular the maintenance of the sharpness of the punch and die.

A similar slope was obtained in the plots of true uniform elongation vs. n_τ for both the ^{59}Ni and the 316 variations. The two data sets are combined in Fig. 5(b) where it is clear that all the data falls on a single line which has a regression slope of 2.35 and an x-axis intercept of 0.05. The corresponding result in the study by Toloczko et al. [5], gave a slope of 2.26 and x-axis intercept of 0.066. In effect, a single linear correlation appears to exist between ε_u and n_τ for a variety of materials, thermomechanical starting states and irradiation-induced microstructures.

4. Conclusions

A shear punch–tensile correlation developed previously from data on unirradiated material has been tested successfully on an extensive database derived from irradiated materials. This correlation has been shown to predict tensile yield and ultimate properties to an acceptable level of accuracy from shear punch data over a wide range of both deformation-induced and irradiation-induced material strengths.

The slope of the tensile yield-effective shear yield strength correlation has been experimentally determined to be ~2 as might be expected from theoretical considerations of the stress state during a SPT. There exists an x-axis offset, however, which is a component of the experimental value of effective shear yield strength. The offset appears to be material-dependent. The offset for a particular set of irradiated materials has been shown to be unchanged from that of the same alloys in the unirradiated condition.

A separate correlation, with different slope and offset parameters can be defined for ultimate tensile strength and effective shear maximum strengths. The offset parameter for the ultimate strength correlation is generally larger than that for the yield strength.

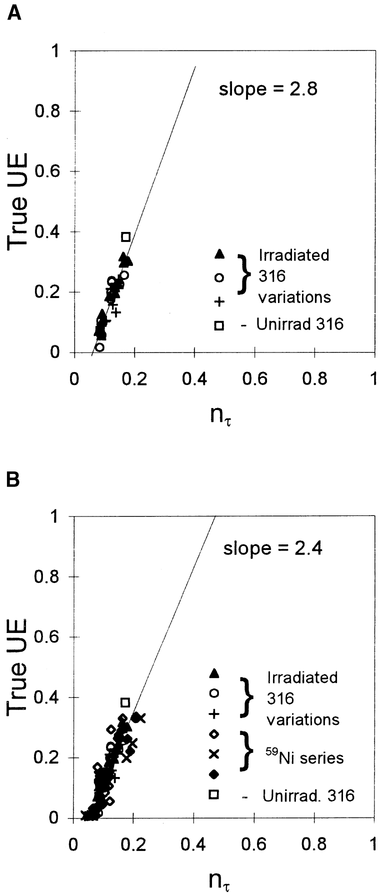

Fig. 5. (a) Correlation between tensile true uniform elongation, ε_u, and a strain hardening exponent, n_τ, for three 316 SS variations and their unirradiated controls. (b) Correlation between ε_u and n_τ for a variety of materials, thermomechanical starting and irradiation-evolved microstructures.

With knowledge of the relevant offset parameter obtained using unirradiated materials, the current correlation allows tensile yield and ultimate strengths of irradiated materials to be predicted from effective shear maximum and effective shear yield strengths with a standard deviation of 50–60 MPa. The correlation becomes more accurate as materials become harder.

Most importantly, the ductility correlation produced from irradiated material data is consistent with that obtained in earlier work from unirradiated materials data. A single slope and intercept can be defined for a range of different materials in both the irradiated and unirradiated condition.

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