THE EFFECT OF FUSION-RELEVANT HELIUM LEVELS ON THE MECHANICAL PROPERTIES OF ISOTOPICALLY TAILORED FERRITIC ALLOYS - **G. L. Hankin (I.P.T.M.E., Loughborough University, England), M. L. Hamilton, D. S. Gelles (Pacific National Northwest Laboratory), and M. B. Toloczko (Washington State University)**

OBJECTIVE

The purpose of this work was to determine the influence of helium level on the mechanical properties of a set of isotopically tailored ferritic alloys following irradiation.

SUMMARY

The yield and maximum strengths of an irradiated series of isotopically tailored ferritic alloys were evaluated using the shear punch test. The composition of three of the alloys was Fe-12Cr-1.5Ni. Different balances of nickel isotopes were used in each alloy in order to produce different helium levels. A fourth alloy, which contained no nickel, was also irradiated. The addition of nickel at any isotopic balance to the Fe-12Cr base alloy significantly increased the shear yield and maximum strengths of the alloys, and as expected, the strength of the alloys decreased with increasing irradiation temperature. Helium itself, up to 75 appm over 7 dpa appears to have little effect on the mechanical properties of the alloys.

PROGRESS AND STATUS

Introduction

It is expected that the most significant difference between fission and fusion reactor environments is the high rate of transmutant helium generation resulting from fusion spectra [1]. In the worst case in a high nickel content alloy, the rate for helium generation in a fast reactor is ~0.5 appm He/dpa which compares with an expected level of ~10 appm He/dpa for iron-based alloys proposed for first wall applications in fusion reactors. Many of the previous experiments devised to study the effect of helium levels relevant to fusion reactor materials used complex alloys which had sometimes experienced different neutron irradiation spectra and flux levels in order to simulate the expected conditions. These experiments were not always successful since potential effects of the helium were masked by the more dominant effects of neutron flux and temperature history [2]. Helium production at a rate of 10 appm He/dpa, can be achieved in HFIR by the addition of 1.5% ^{59}Ni [3].

A recent study [4] reported on a simple, one variable experiment which was devised in order to study the effects of different helium levels on the microstructures that evolved in a set of isotopically tailored ferritic alloys, nominally of composition Fe-12Cr-1.5Ni. The rate of helium evolution was varied from 0.3 to 10.7 appm/dpa without changing the neutron spectrum or the atomic displacement rate, by varying the isotopic content of the nickel. The same composition and initial microstructure was maintained for the nickel containing alloys. The first Fe-12Cr-1.5Ni variant contained the ^{59}Ni isotope which undergoes an (n,a) reaction to form helium. This idea had been tested and proven in a previous series of FFTF irradiations on Fe-Cr-Ni austenitic alloys [5]. The second alloy contained ^{60}Ni which produces very little helium (~2 appm He after 7 dpa) and the third alloy contained natural nickel which produces an intermediate level of helium after the delayed development of ^{59}Ni. The fourth alloy, which was included to clarify the role of nickel on the properties of these alloys, contained no nickel.

This paper reports on the shear punch testing of the same set of alloys. Of particular interest are the trends in some of the mechanical properties of the ferritic alloys as a function of helium content.

Experimental Procedure
Specimens were irradiated side-by-side in the HFIR-MFE-JP23 experiment at four different temperatures to ~7 dpa. Based on results from previous irradiation experiments, it is expected that sufficient dose to initiate void swelling in ferritic/martensitic alloys would have been experienced by this point [4].

The shear punch test is essentially a blanking operation which is common to sheet metal forming. 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 load on the punch is measured as a function of punch travel, which is taken to be equivalent to the cross head displacement [6]. This assumes that the test machine and punch are completely stiff relative to the response of the test specimen. A plot of punch load versus punch displacement was obtained for each specimen.

With the exception of one set of irradiated aluminium alloys [8], shear punch testing has thus far only been carried out on unirradiated materials. A new test facility was set up and a detailed procedure was written to accommodate the shear punch testing of highly irradiated specimens. All tests were conducted under ambient conditions and the results of each test were recorded by computer and simultaneously recorded on a chart recorder.

The curve obtained from a shear punch test is of a similar form to that obtained from a tensile test. Initially a linear relationship exists between load and punch displacement during which no plastic deformation occurs. This is followed by a deviation from linearity or yield point when permanent penetration of the punch into the specimen occurs. Beyond the yield point, further deformation forms a shear process zone between the die and punch. Work hardening compensates for thinning until a maximum load is achieved [6]. The points of interest on the curve were the yield load and maximum load. Effective shear yield strength (τ_{sy}) and an effective maximum shear strength (τ_{sm}) can be evaluated from these values, respectively, by the following equation [7]:

$$\tau_{sy,sm} = P/(2\pi rt)$$

where P is the appropriate load, r is the average of bore and punch radii and t is the specimen thickness. Previous work has shown that an empirical relationship can be developed between data from shear punch testing and that from tensile testing [7,8,9]. In this instance, however, no tensile data were available and the shear punch test was used only as a tool to identify trends in the mechanical properties that might occur as a result of differing helium levels.

Results
Two tests per specimen condition were performed with good reproducibility in the data: effective shear strength typically varied by no more than 30 MPa between duplicate specimens. Figure 1 shows a summary of τ_{sy} as a function of helium content. Figure 2 shows a similar plot for τ_{sm}. Data from the unirradiated material is included in Figures 1 and 2 with the corresponding data from the irradiated material.

It is evident from the plots of τ_{sy} and τ_{sm} that the addition of nickel to the Fe-12Cr base alloy significantly increases the strength of both the unirradiated and the irradiated alloys, especially for irradiation temperatures of 300 and 400°C. The yield and maximum shear strengths are increased by ~100% for the unirradiated condition, a result which is independent of the nickel isotope balance used.

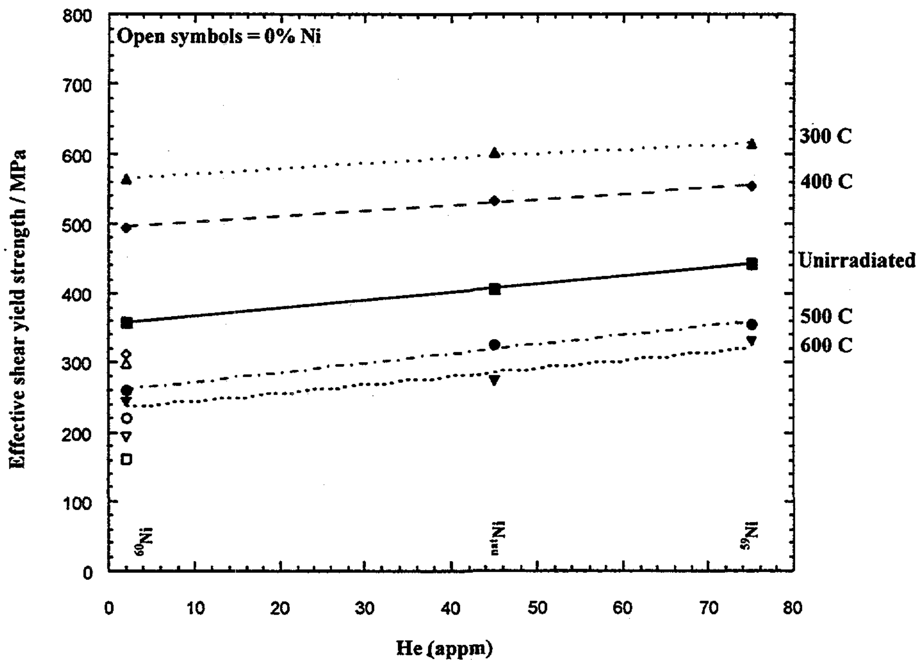

Figure 1 - Effective shear yield strengths (τ_{sy}) in Fe-12Cr-1.5Ni as a function of helium content (an open symbol signifies the control alloy [Fe-12Cr] at the same condition as the corresponding filled symbol).

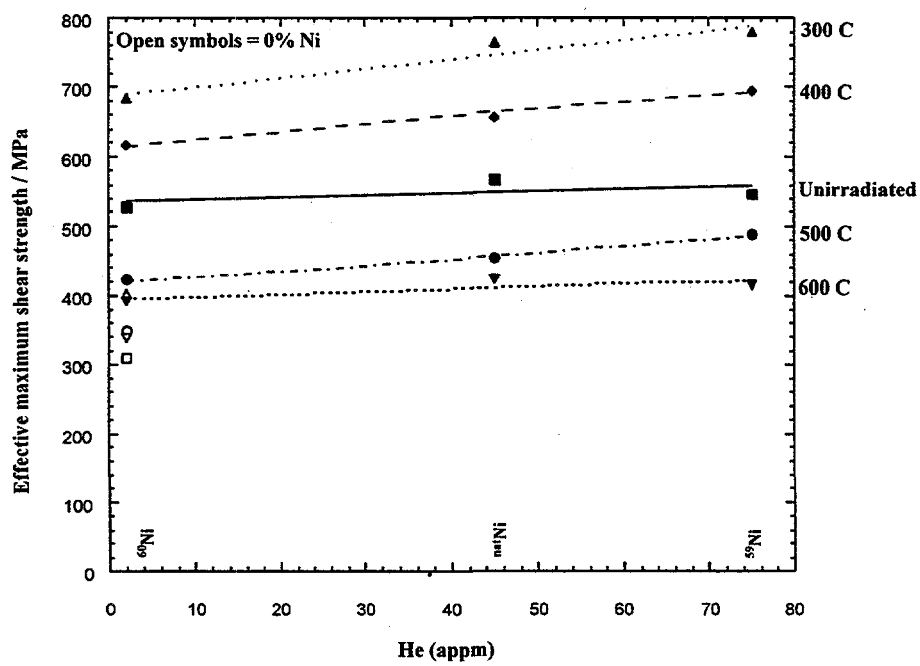

Figure 2 - Effective maximum shear strengths (τ_{sm}) in Fe-12Cr-1.5Ni as a function of helium content (an open symbol signifies the control alloy [Fe-12Cr] at the same condition as the corresponding full symbol).

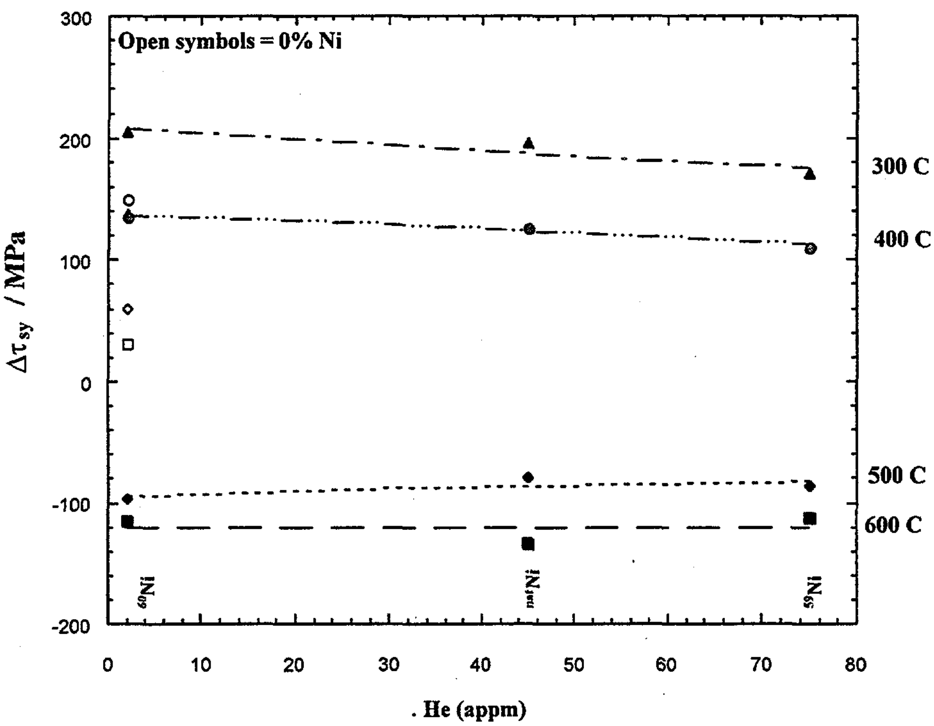

Figure 3 - Change in τ_{sy} with respect to the unirradiated condition as a function of helium content.

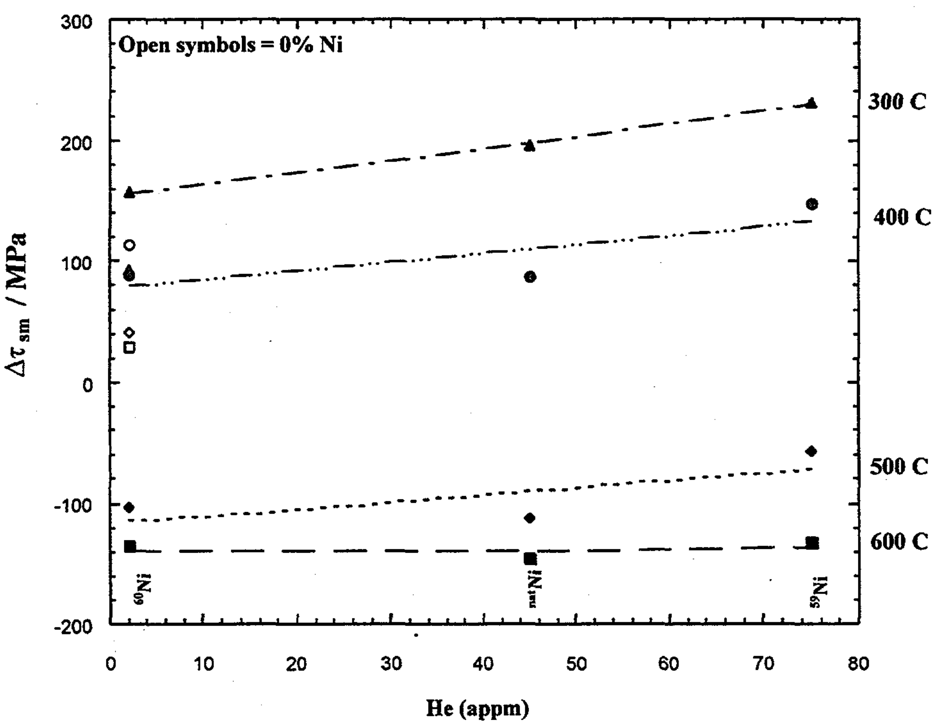

Figure 4 - Change in τ_{sm} with respect to the unirradiated condition as a function of helium content.

The strength of all alloys decreased with increasing irradiation temperature. The highest strength was observed for alloys irradiated at 300°C. The alloys irradiated at 500 and 600°C experienced an overall decrease in strength when compared to the unirradiated condition.

A small increase in both τ_{sy} and τ_{sm} is observed with increasing helium content in the irradiated alloys. Since the same trend is echoed in the data for the unirradiated material, however, it cannot be attributed to the helium level, but rather to another factor inherent to the alloys. Figures 3 and 4 show the change in τ_{sy} and τ_{sm} with respect to the unirradiated condition ($\Delta\tau_{sy}$ and $\Delta\tau_{sm}$ respectively) versus helium content for each irradiation temperature. While a shallow negative gradient is observed for the lower irradiation temperatures for $\Delta\tau_{sy}$, the trend is reversed in Figure 4 for $\Delta\tau_{sm}$.

Discussion

It is clear from Figs. 1 and 2 that nickel additions significantly increase τ_{sy} and τ_{sm} of the alloys before irradiation. This is true for all irradiation temperatures as well as in the unirradiated condition, which suggests that the strengthening action was present at least in part, prior to irradiation and can probably be attributed primarily to solution strengthening/precipitation hardening due to the addition of nickel. The slight variability observed in the strength for each isotopic variation is currently unexplained, but may arise from variability in impurity levels associated with the isotopic additions.

Irradiation at 300 and 400°C both caused an increase in strength when compared to the unirradiated material with the greatest strengthening occurring at 300°C. This is in agreement with the microstructural analysis carried out by Gelles [4] on the same set of alloys. The microstructure of the material irradiated at 300°C exhibited a dense distribution of fine precipitates, small voids and small dislocation loops. Each of these features would be expected to produce an increase in the strength of the alloy. The material irradiated at 400°C showed a more coarse microstructure, with larger and fewer precipitates and fewer, but more developed, dislocation loops. The material irradiated at 500 and 600°C showed an overall reduction in strength when compared with the unirradiated condition. Although the microstructures have not been studied for the alloys irradiated at 500 and 600°C, it is expected that further coarsening and increased loop and precipitate growth will have occurred.

The plot of $\Delta\tau_{sy}$ versus helium content (Fig. 3) shows a shallow positive gradient for materials irradiated at the lower temperatures. This trend is reversed, but has a slightly steeper gradient, in the plot of $\Delta\tau_{sm}$ versus helium level (Fig. 4). The variation in $\Delta\tau_{sy}$ over the range of helium levels for irradiation at a given temperature is only ~30 MPa, which is essentially the same as the scatter in the data for a given test condition (±20 MPa). It is therefore difficult to draw any conclusions, other than that helium levels up to 75 appm have little or no influence on the mechanical properties over the range of temperatures considered.

CONCLUSIONS

The shear punch testing of a series of isotopically tailored Fe-12Cr-1.5Ni ferritic alloys showed that helium levels up to 75 appm have little, if any, effect on the effective shear yield and maximum shear strengths. The strengthening effect of nickel was evident prior to irradiation and the strength of the irradiated Fe-12Cr-1.5Ni ferritic alloys shows a strong dependence on irradiation temperature, decreasing with increasing irradiation temperature.

FUTURE WORK

Chemical analysis of the unirradiated controls is planned to investigate the possible effect of variation in impurity levels.

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