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Irradiation Creep in Type 316 Stainless Steel and U.S. PCA with Fusion Reactor He/dpa Levels*

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Abstract

Irradiation creep was investigated in type 316 stainless steel (316 SS) and U.S. Fusion Program PCA using a tailored spectrum of the Oak Ridge Research Reactor in order to achieve a He/dpa value characteristic of a fusion reactor first wall. Pressurized tubes with stresses of 20 to 470 MPa were irradiated at temperatures of 330, 400, 500, and 600°C. It was found that irradiation creep was independent of temperature in this range and varied linearly with stress at low stresses, but the stress exponent increased to 1.3 and 1.8 for 316 SS and PCA, respectively, at higher stresses. Specimens of PCA irradiated in the ORR and having helium levels up to 200 appm experienced a 3 to 10 times higher creep rate than similar specimens irradiated in the FFTF and having helium levels below 20 appm. The higher creep rates are attributed to either a lower flux or the presence of helium. A mechanism involving interstitial helium-enhanced climb is proposed.

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1. Introduction

Irradiation creep is important in structures under irradiation. Stresses introduced by swelling are often relieved by irradiation creep; however, an imbalance of the two processes can lead to phenomena such as fuel pin bowing in fission reactors. In fusion reactors, irradiation creep will be important in determining deformation of the first wall and blanket structures in response to swelling stresses as well as thermal and primary load stresses. In a fusion reactor, irradiation creep will take place in the presence of high levels of helium, the effect of which is unknown. Irradiation creep has been studied in fast reactors, where the helium production rate is very low, as well as in mixed-spectrum reactors where the helium production rate is very high. However, irradiation creep has not previously been studied under conditions where the fusion reactor level of helium per atomic displacement (He/dpa) is achieved. The present experiment achieved this goal by tailoring the neutron spectrum of the Oak Ridge Research Reactor (ORR). In order to establish the effect of helium, the creep rates observed in the spectrally tailored experiment will be compared with creep results obtained from irradiating the same heat of PCA in the Fast Flux Test Facility (FFTF).

2. Experimental Procedure

In order to achieve the fusion reactor He/dpa level of about 12 appm/dpa for type 316 stainless steel (316 SS), the ORR irradiation vehicle was provided with a removable core piece. The irradiation began with water surrounding the irradiation capsule in order to rapidly burn in ^{59}Ni with the resulting high thermal flux. After 6.5 dpa, an aluminum core piece replaced the water, and after a total of 8.5 dpa, hafnium replaced the aluminum. With this progression, a He/dpa ratio of 12 was achieved after about 6 dpa, and this ratio remained for the duration of the irradiation.

The specimens consisted of pressurized tubes 25.4 mm in length and 4.57 mm in diameter. The tubes were pressurized with helium to effective stress levels [1] of 20 to 470 MPa depending upon irradiation temperature. The alloys studied were 316 SS (HT X15893) of composition in weight percent except where noted, as follows: 4 appm B, 0.06 C, 0.3 Co, 17.4 Cr, 0.3 Cu, 1.7 Mn, 2.1 Mo, 0.06 N, <0.05 Nb, 12.4 Ni, 0.037 P, 0.18 S, 0.67 Si, 0.01 Ta, <0.05 Ti, bal Fe, and PCA (HT K-280) of composition: 0.05 C, 14.0 Cr, 1.8 Mn, 2.3 Mo, 0.01 Nb, 16.3 Ni, 0.01 P, 0.44 Si, 0.24 Ti, bal Fe. The specimens were fabricated from drawn tubing with residual cold-work levels of 20 and 25% for the 316 SS and PCA, respectively. Four irradiation temperatures were investigated: 330, 400, 500, and 600°C. Temperature control was achieved by immersing the specimens in NaK surrounded by a gas gap. Based upon the temperature of the thermocouples in the specimen chambers, the composition of the gas in the control gap was varied from pure helium to pure argon to control temperature. The specimens were removed from the reactor for examination at damage levels of 5 and 12 dpa and helium levels of 44 and 160 appm for 316 SS and 56 and 200 appm for PCA.

The tubes were profiled with a non-contacting laser micrometer system with a precision of ±250 nm. Although the complete tube profiles were used to evaluate the specimens, the average diameter of the central three-fifths of each tube was used in the analysis of the data. Swelling measured by immersion density on unpressurized tubes was subtracted from the creep data.

3. Results

The effective creep strain as a function of effective stress is shown for both 316 SS and PCA in Figs. 1 and 2, respectively. For stresses below about 350 MPa, both alloys exhibit a nearly linear dependence of creep strain on stress with the stress exponents having an average value of 0.96 for each alloy when averaged over the four temperatures. At higher stress levels the curves become non-linear, with the stress exponent for 316 SS becoming 1.3 and the stress exponent for PCA becoming 1.8. The slope appears to be still increasing at the highest stress levels investigated. Data from tubes that appear to have failed were not considered.

In order to evaluate the effect of helium on irradiation creep, the data in the present study were compared with data from Puigh [2] on pressurized tubes of the same heat of PCA irradiated in the FFTF. Because of the hard spectrum of this reactor, the helium production rate is only 0.28 appm/dpa [3].

The ratio of creep strain to stress is plotted as a function of dpa in Fig. 3 for the present study in the ORR as well as for the FFTF at 400°C. It is apparent that the creep rate is higher for the material irradiated in the ORR. The same behavior is observed at 500°C (Fig. 4) and 600°C (Fig. 5), although scatter in the data makes the comparison less clear at the highest temperature.

4. Discussion

The linear stress dependence exhibited by the data in Figs. 1 and 2 at low stresses is the commonly observed behavior especially at low stresses [4,5]. It is the result characteristic of the stress-induced preferential absorption (SIPA) mechanism of irradiation creep [6]. An increasing stress exponent at higher stresses has also been previously observed [2,7,8]. Hudson and Nelson attribute this behavior to thermal creep at 500°C and Wassilew attributes this behavior to a transition from the SIPA mechanism to a climb-enabled glide mechanism [7,8]. The climb-enabled glide mechanism proposed by Mansur [9] predicts a quadratic dependence on stress. The present data show a stress exponent of 1.3 for 316 SS and 1.8 for PCA at 330°C. If this higher exponent results from a transition in mechanism, the fact that it is lower than two could result from the fact that the transition is not yet complete at the stress levels investigated. It is also possible that both mechanisms operate throughout the entire range of stress, but the quadratic dependence only becomes apparent at higher stresses [9]. Wassilew observed that the transition to quadratic stress behavior occurs at lower stress levels as temperature increases [8]. Since the significantly lower stresses used for the higher temperature irradiations in order to prevent rupture were probably below the transition stresses, this phenomenon was not observed in the present investigation. However, such behavior might be expected since increased thermal activation of pinned dislocations associated with higher temperatures could result in glide at lower stresses.

The higher creep rates of ORR-irradiated material compared with FFTF-irradiated material shown in Figs. 3 through 5 will now be considered.

Since the PCA specimens used in Puigh's work were fabricated from the same tubing used in the present investigation, the difference in creep rate can only result from differences in the irradiation environment. Four possibilities are apparent: the fluence level, the flux level, the energy spectrum, and the presence of helium. As seen from the plots of Figs. 3 through 5, especially at 400°C, the FFTF data are well described by the straight line least squares fit shown, and the extrapolation in dpa to the data from this study is not a large one. The difference in the fluxes deserves careful consideration. In specimens irradiated in the Dounreay Fast Reactor, Lewthwaite and Mosedale observed an increase in creep rate per dpa with decreasing flux [10]. Straalsund observed no effect in austenitic stainless steels irradiated in the EBR-II. McElroy et al. [11] on the basis of fast reactor data concluded that there is an increase in creep rate with increasing flux but that the effect is small, and Mosedale and Lewthwaite observed a similar trend in annealed material [12]. Wassilew also observed an increased creep rate at higher flux levels [8]. Since a higher flux results in a higher defect recombination rate, theory predicts that the irradiation creep rate per unit fluence should decrease with increasing flux, provided that the microstructure shows no dependence on flux. Clearly the effect of flux on irradiation creep is not yet resolved. Thermal neutrons have been shown to be more effective in producing defects than fast neutrons [13]. This effect could result in a higher level of irradiation creep; however, the increment of irradiation creep would be expected to diminish as the spectrum was hardened during the course of the irradiation in the ORR. The opposite was observed.

The remaining possibility for the observed increase in creep rate in the present experiment is the effect of helium. The helium production rates for the ORR spectral tailoring experiment and the FFTF differ by a factor of about 60, and the creep rates are increased by a factor of 3 to 10. The mechanism by which the helium might increase the creep rate is not determined as yet. One possibility is that helium affects the microstructural sink strengths, which in turn affect the fates of point defects resulting in altered creep rates [9]. Another possibility that is proposed depends more directly on the presence of helium. It is known that helium exists in the lattice both as an interstitial and as a substitutional solute [14] as well as being trapped in clusters and cavities. It is suggested that a portion of the helium produced by the irradiation will contribute to the interstitial population which should contribute to dislocation climb and thus to irradiation creep. In this process the helium atoms that diffuse to the dislocations as interstitials, producing a net climb of the dislocation, then occupy lattice sites in the same manner as self-interstitials. In the presence of a stress, climb of the dislocation might be sufficiently rapid to prevent the agglomeration of enough helium to form bubbles along the dislocation.

The question that must now be addressed is whether the number of interstitial helium atoms is significant compared to the population of self-interstitials. The fraction of the helium concentration that will reside in interstitial sites can be estimated. To do this, a method used by Mansur et al. will be followed [15]. The rate equation for the production and loss of helium interstitials can be written as:

$$\underset{(1)}{\tau_s^{-1} C_S} + \underset{(2)}{G'\Omega C_S} + \underset{(3)}{R_r C_i C_S} - \underset{(4)}{K_{He} C_v C_{He}} = 0 \quad . \qquad (1)$$

Term (1) is the production rate of interstitial helium by thermal release of substitutional helium; term (2) is the displacement rate of substitutional helium; term (3) is the rate of exchange of self-interstitials and substitutional helium, producing a helium interstitial; term (4) is the loss rate of interstitial helium converted to substitutional helium through capture by vacancies. The loss to sinks, such as dislocations and grain boundaries, is neglected. All terms are per unit volume. The necessary expressions are interpreted as follows:

$\tau_s = \nu^{-1} \exp[(E^b_{He-v} + E^m_{He})/kT]$ is the mean residence time of helium in a vacancy before thermal release, ν is the attempt frequency which will be taken to be b^2/D^o_{He} where b is the Burgers vector and D^o_{He} is the coefficient in the diffusivity of substitutional helium. E^b_{He-v} is the binding energy between a substitutional helium atom and a vacancy and E^m_{He} is the energy of migration of helium.

G' is the generation rate of interstitial helium by direct displacement per unit concentration of substitutional helium. The symbol $R_r = 4\pi r_r D_i$ is the coefficient of replacement where a self-interstitial dislodges a substitutional helium atom; r_r is the radius of the replacement volume.

$K_{He} = 4\pi r_{He-v} (D_{He} + D_v)$ is the capture coefficient of a vacancy for an interstitial helium atom; r_{He-v} is the radius of the capture volume. C_s is the concentration of substitutional He, Ci is the concentration of self-interstitials, C_v is the concentration of vacancies, and C_{He} is the concentration of interstitial helium.

What was felt to be reasonable values for the above parameters were used in the calculation; the values appear in Table 1. The result is that the ratio C_{He}/C_S ranges from 10^{-8} to 10^{-5} over the range of 300 to 600°C. If a helium concentration of 100 appm were in substitutional sites, the interstitial helium concentration then is in the range of 10^{-12} to 10^{-9} atom fraction. This is to be compared with the self-interstitial population for which 10^{-12} is a representative value. Therefore, the calculation shows that the generated helium can make a significant contribution to the total interstitial population so that the mechanism is considered a plausible one. Considering the very large uncertainties involved in this calculation, it is considered only an attempt to determine if the suggested mechanism is possible.

5. Summary and Conclusions

1. Irradiation creep in the range of 330 to 600°C is independent of temperature in the presence of fusion reactor-like helium generation rates in the austenitic steels studied.

2. Irradiation creep strain is linear in stress at low stresses but increases with a stress exponent approaching two at high stresses. This was most apparent in PCA but was observed only at 330°C due to the limited range of stress at the higher temperatures.

3. The irradiation creep rate is three to ten times higher for the high-helium ORR irradiation, where the He/dpa value is about 12, compared with FFTF irradiation, where the He/dpa value is only 0.28 appm/dpa.

4. The higher creep rate is believed to result from either the lower flux in the ORR experiment or from the higher level of helium.

5. A mechanism of helium-assisted climb is proposed to account for the increase in creep rate due to helium.

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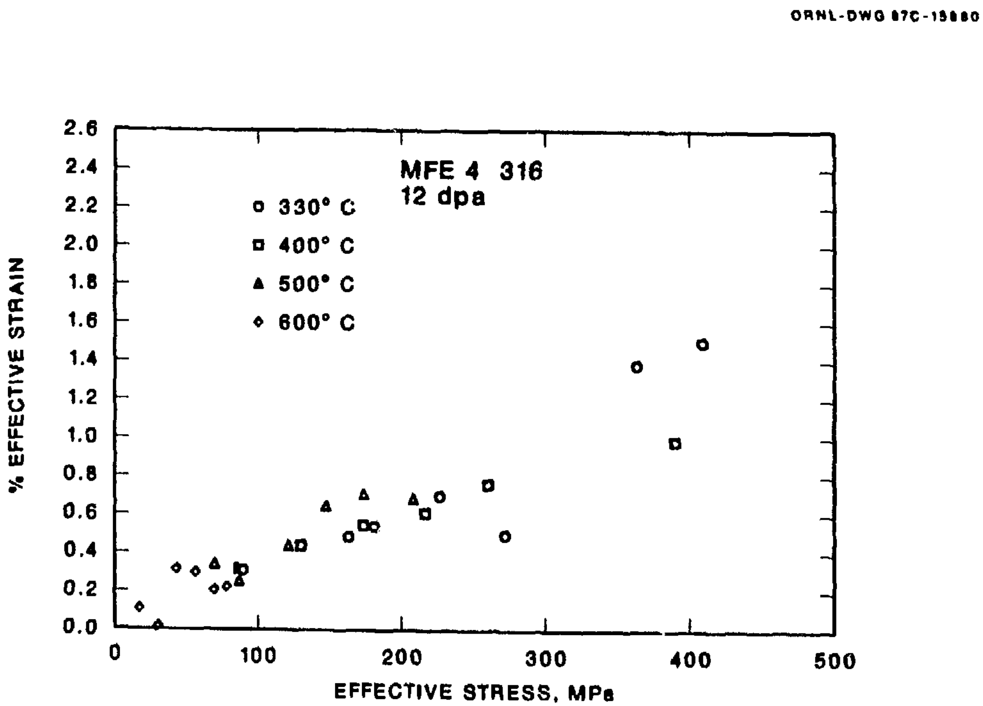
List of Figures

Table 1. Representative values of parameters used in estimation of interstitial helium concentration

Values	Reference
$b = 5$ Å	
$D^{o}_{He} = D^{o}_{v} = 1.4 \times 10^{-2}$ cm²/s	[16]
$E^{b}_{He-v} = 2.5$ eV	
$E^{m}_{He} = 0.15$ eV	
$r_{He-v} = 5$ Å	
$D_{v} = 1.4 \times 10^{-2} \exp(-1.38 \text{ eV}/kT)$	[16]
$D_{He} \sim D_{H}(Ni) = 4.8 \times 10^{-3} \exp(-0.41 \text{ eV}/kT)$	[17]
$G' = 2.7 \times 10^{-7}/\text{cm}^{-3}\ \text{s}^{-1}$	(ORR experimental data)
$C_{v} = 10^{-6}$ atom fraction	
$C_{i} = C_{v} \frac{D_{v}}{D_{i}}$	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330° C
400° C
500° C
600° C
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EFFECTIVE STRESS, MPa
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0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
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2.4
2.6
0
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200
300
400
500

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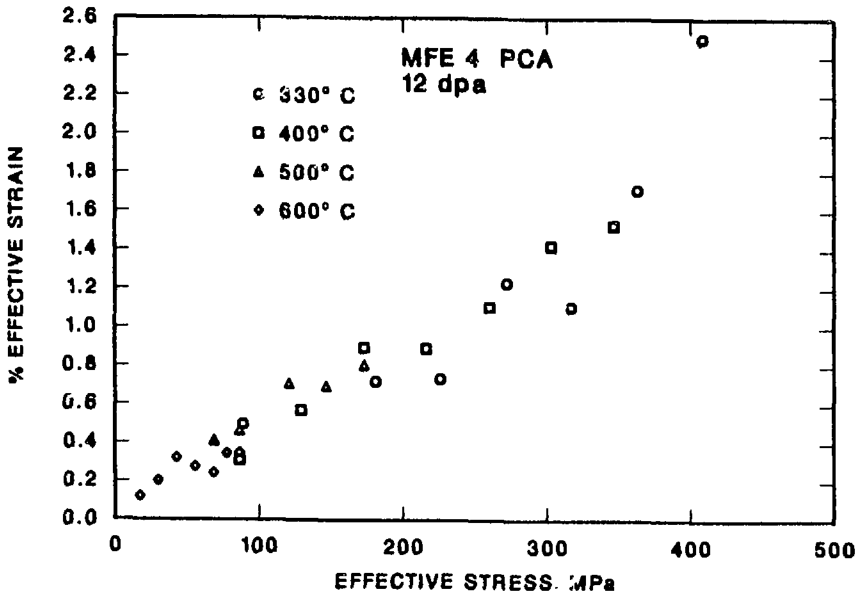

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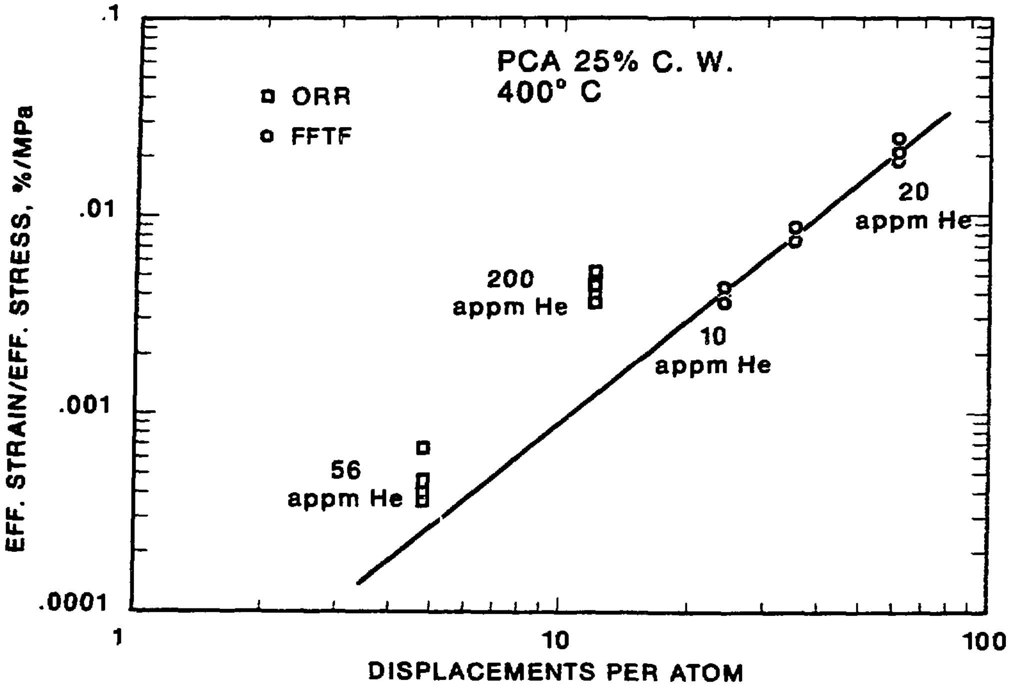

Fig. 3

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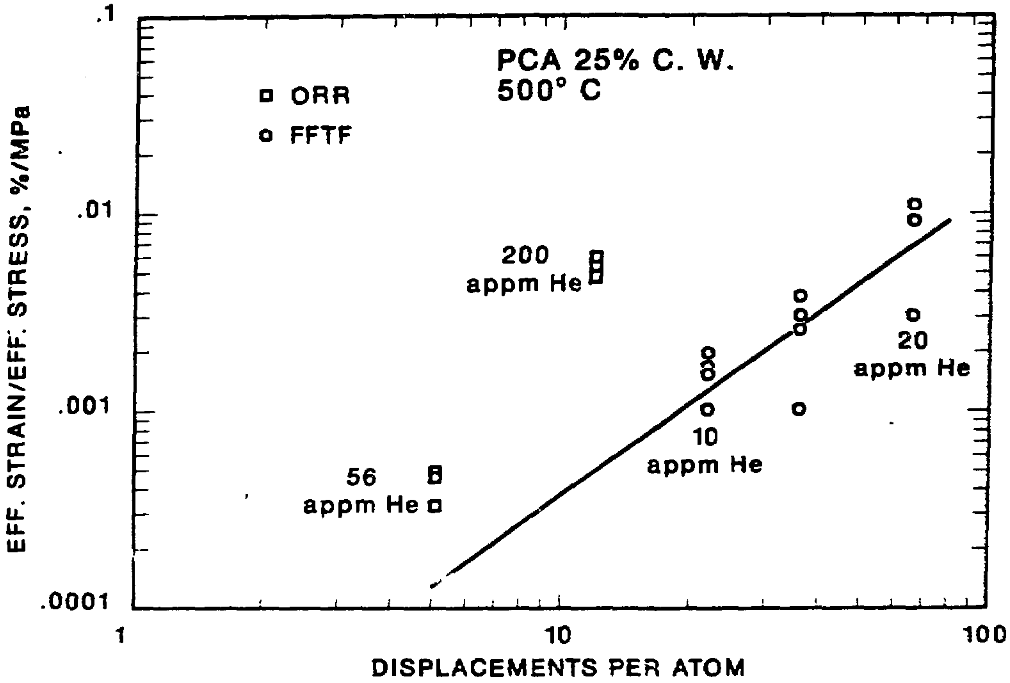

Fig. 4

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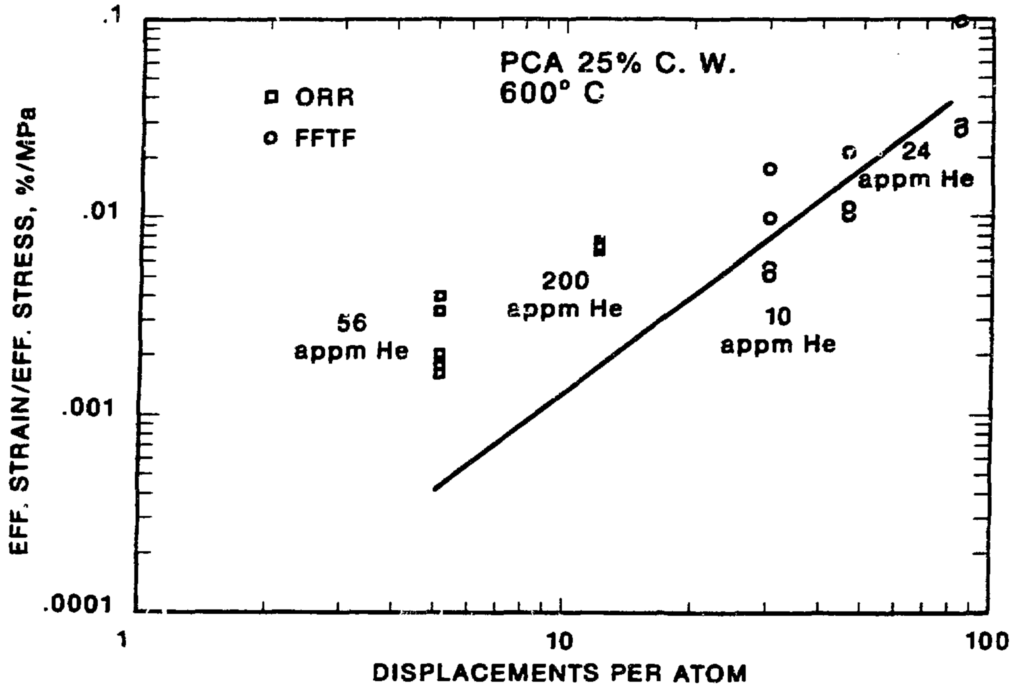

Fig. 5

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