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TENSILE PROPERTIES OF JPCA AND JFMS IRRADIATED IN JMTR BY MEANS OF MINIATURIZED SPECIMEN TESTING*

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Synopsis

In the research and development of miniaturized specimen technology, consideration of specimen size effect is the key issue. In this work, tensile tests were studied with variations of specimen size around the standard mini-tensile specimen in the Japanese fusion materials program.

The materials used were JPCA (modified 316 SS) and JFMS (modified 10Cr-2Mo dual phase steel). Microstructure has been controlled to clarify the effect of grain size for the former and the effect of ferrite/martensite ratio for the latter. Neutron irradiations of post-irradiation deformation response, microstructure prior to and after deformation were examined by transmission electron microscopy.

The effects of specimen thickness and aspect ratio(thickness/width) on tensile properties are studied. New scaling equations to evaluate valid yield strength and tensile strength from small specimens with thickness less than the critical thickness, t_c, are proposed. The origins of specimen size effects from a microstructural viewpoint are also discussed.

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I. Introduction

There has been a long history of attempts to reduce the specimen size for mechanical testing, particularly for the testing of irradiated specimens[1-4]. Major motivations to establish small specimen testing methods are limitations in irradiation space and radiation dose to personnel in post-irradiation tests. Recent efforts in alloy development for nuclear fusion reactors have expanded the interest in reducing specimen sizes.

In the Japanese Monbusho fusion materials program , a standard small tensile specimen with gauge section dimensions of 1.2x5.0x0.25 mm has been proposed and has been utilized in the irradiation programs in RTNS-II, JOYO, JMTR and FFTF/MOTA by major participants from Japanese universities. This is much smaller than the SS-3 specimens used in the US fusion programs.

The objectives of this investigation were to establish the basis for smaller specimen tensile testing, to apply the method to irradiated ferrous materials and ultimately for neutron irradiated materials in general.

II. Experimental

The materials used were the austenitic stainless steel, JPCA (Fe-0.06C-16.22Ni-14.57Cr-2.37Mo-0.24Ti) and the JFMS (Fe-0.050-0.94Ni-9.85Cr-2.31Mo0.12V-0.06Nb)[5-7]. They were heat treated to get a variety of grain sizes(26-171μm for JPCA) and ferrite/martensite volume ratios(0.32-0.37 for JFMS) as the variable material parameters.

Two types of standard tensile specimens, T1 and T2, are used, where the sizes of the gauge section are 1.2(w)x5.0(l)x0.25(t) mm for the former and 2.4(w) x10(l)x0.5(t) mm for the latter. Blank forms are machined from the thick plate with the tensile specimen profile, and individual specimens are saw cut to the desired thickness from the blank form. The surface is polished by wet Emery paper. In this work, specimen thickness was the key variable. The specimen thickness to the specimen width ratio, or aspect ratio, was varied over a range from 0.01 to 10. 3.0 mm disk-shaped specimens for transmission electron microscopy are punched from the T-2 specimens after testing. Neutron irradiation were performed in JMTR at Oarai with a neutron flux of $1.6\text{x}10^{17}$ n/m^2s and a nominal irradiation temperature of 430K. Irradiation times were 24, 72, 144 and 288h. The displacement damage rate was calculated to be 1.99 mdpa/day from the SPECTER-code.

III. Results and discussion

(1) Specimen size effects in unirradiated materials

To obtain basic knowledge, specimen size dependence of mechanical properties were investigated for unirradiated specimen. Yield strength is known to be thickness independent for thickness larger than a critical thickness, t_c[2-4]. The critical thickness for ferrous materials is about 6 to 10 times the average grain size. In this work, specimen width was varied with specimen thickness. Fig.1 suggests that specimen width does not affect yield stress and that only specimen thickness affect the results for $t<t_c$. The critical thickness for JPCA (indicated by P in the figure) and JFMS (indicated by F) are about 6 times the average grain size for the former and also 6 times the average ferrite phase diameter for the latter. For the specimens with the thickness t, smaller than the critical thickness t_c, the test results, $\sigma_y(m)$ is correlated with the yield strength of the bulk specimen, $\sigma_y(b)$, as follows:

$$\sigma_y(m) = \sigma_y(b)-\alpha(1/t-1/t_c)\kappa_y d^{1/2}, \quad (1)$$

where d is the average grain diameter, κ_y and α are material and shape constants, respectively. This equation can be derived from Petch's equation and a simple rule of mixture using the matrix strength and grain or phase-boundary strength.

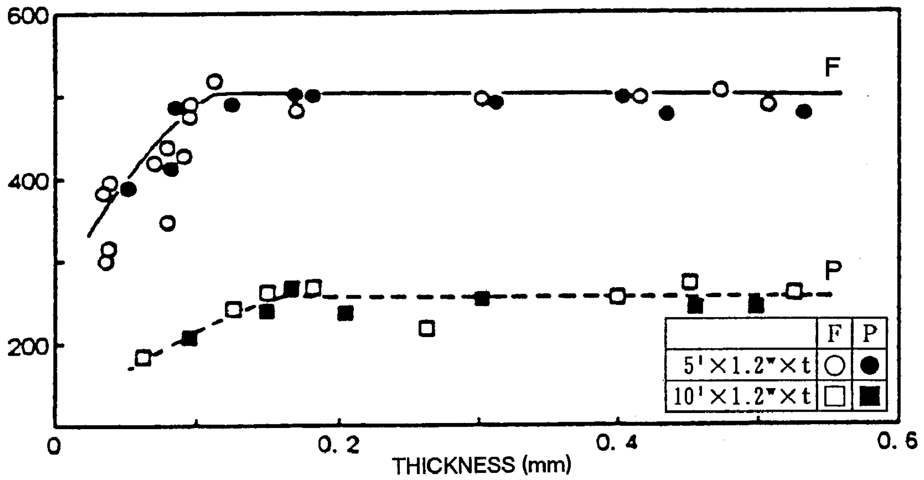

Fig. 1. Specimen thickness dependence of yield stress with variation of specimen width (P:JPCA, F:JFMS).

In a previous paper [8], the critical thickness for ultimate stress was found to be affected by specimen width. This is also confirmed in this work. By plotting ultimate stress data against aspect ratio(specimen thickness to width ratio), as shown in fig. 2, the size effect on ultimate stress can be fitted to the same trend line. A similar dependence of ultimate strain(strain at load maximum) on aspect ratio is shown in fig. 3. The work hardening coefficient was found to be quite independent of specimen thickness and width. These are qualitatively consistent behaviors because plastic deformation is restrained as a function of aspect ratio, but the yield phenomenon is controlled by the weakest path to initiate yielding.

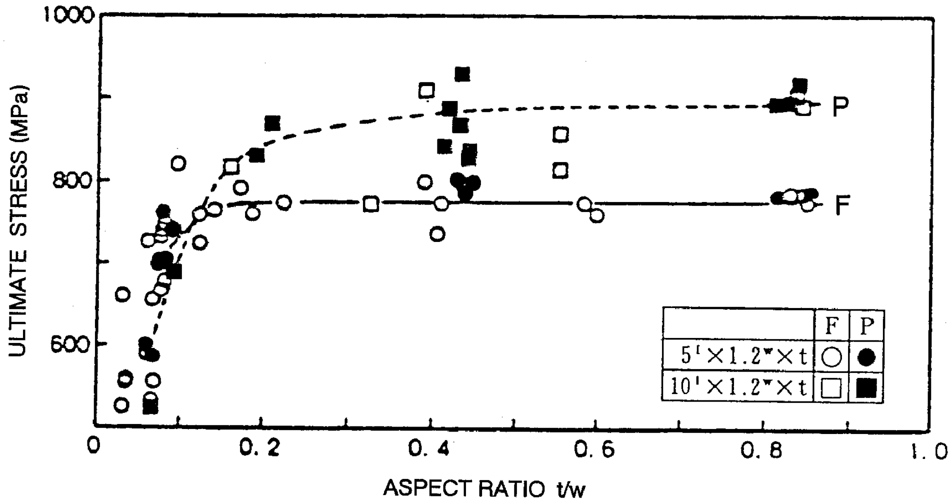

Fig. 2. Aspect ratio (specimen thickness to width ratio) dependence of ultimate stress.

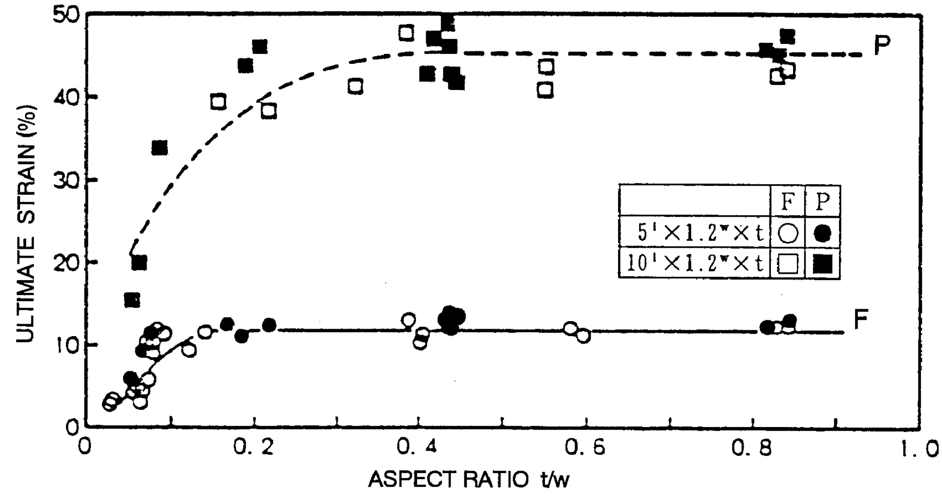

Fig. 3. Aspect ratio (specimen thickness to width ratio) dependence of ultimate strain.

(2) Specimen size effects in neutron irradiated materials

The effect of neutron irradiation on the specimen thickness dependence of yield stress for JPCA and JFMS is shown in fig.4. Although radiation hardening is detected, the thickness dependence of yield stress is not affected, that is t_c is not changed by irradiation. This can be understood by the fact that at the low neutron exposure, radiation hardening is caused by matrix hardening, not by grain boundary hardening. Ultimate stress and strain are also dependent on neutron dose. Fig.5 shows the aspect ratio dependence of ultimate strain.The critical thickness, $t_{c,}$, increases at 24 mdpa. For specimens with thickness smaller than t_c, ultimate strain becomes strongly dependent on aspect ratio, decreasing more for the smaller specimen size even with the same aspect ratio, as reported elsewhere [8]. One probable origin of this size effect is dislocation channeling, observed in the JPCA specimens irradiated to 24 mdpa. Thus at higher neutron exposure, the size effects may become more significant than observed in this experimental condition.

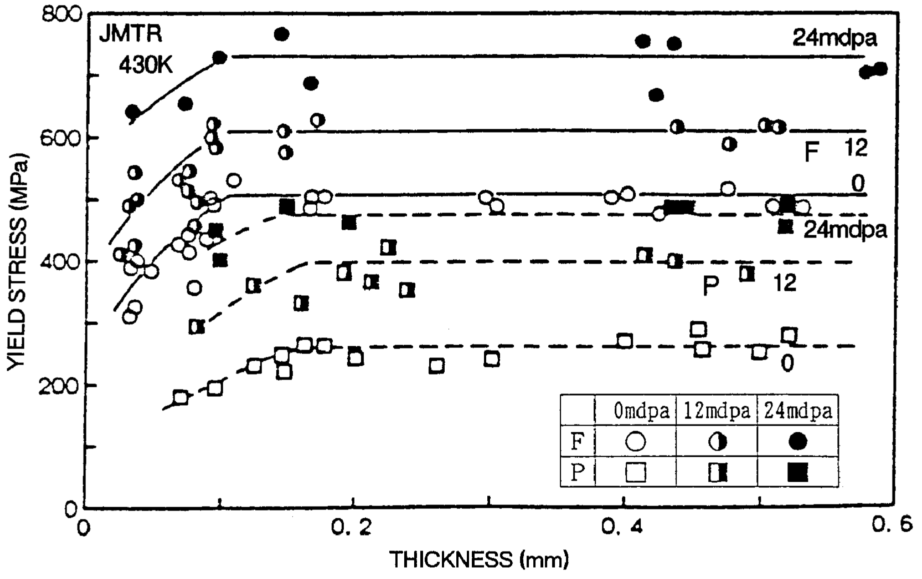

Fig. 4. Effect of neutron irradiation on specimen thickness dependence of yield stress.

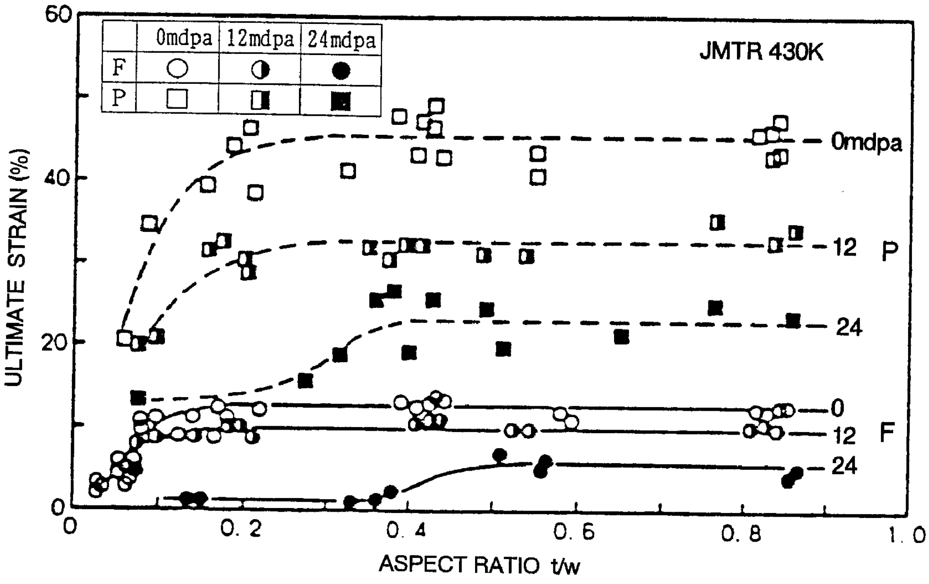

Fig. 5. Effect of neutron irradiation on specimen thickness dependence of ultimate strain.

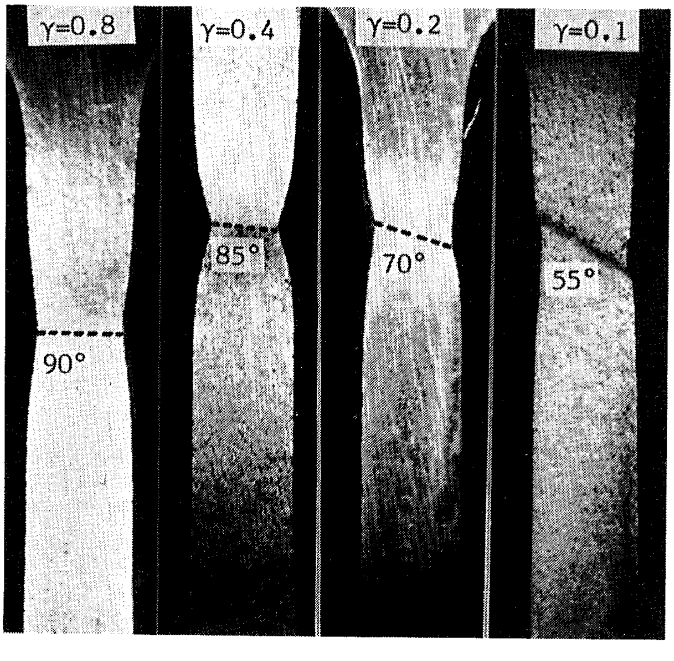

Fig. 6. Appearance of necking angle with variations of aspect ratio.

(3) Deformation necking and anisotropy of deformation strain

Necking takes place for ductile materials like the materials used here, and the necking angle to the tensile axis changes with the specimen aspect ratio, as shown in fig.6. The necking angle, θ, is determined from the criterion of zero strain rate along the necking line for localized necking and is obtained under the constant volume condition, using Mohr's stress circle as,

$$\cos 2\theta = -3/(1+2\kappa) \quad (2)$$

where κ is the ratio of strain in the thickness and width directions, ϵ_t/ϵ_w.

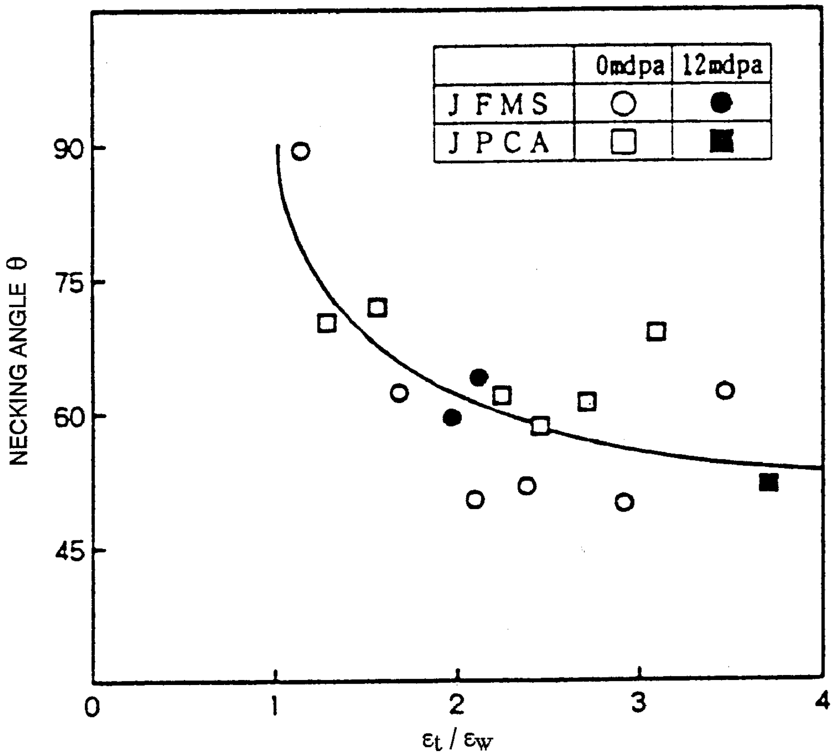

Fig. 7. Dependence of necking angle on anisotropy of deformation strain (solid line after eq. (2)).

The κ value increases with decreasing aspect ratio and this value has a tendency to be increased with increasing neutron dose at fixed aspect ratio. The minimum specimen thickness to give κ value of unity is roughly half the specimen width, which is about 1.5 times larger than the critical thickness for ultimate stress and uniform strain. This result coincides well with the result of Storen and Rice [9]. The dependence of necking angle on κ is shown in fig.7. The solid line in the figure is the calculated line from eq.(2). Coincidence between the experimental value and the calculated value was observed for both unirradiated and irradiated specimens. The experimental results obtained in this work suggests that necking angle, and hence κ value, are good indices of specimen size effects on mechanical properties.

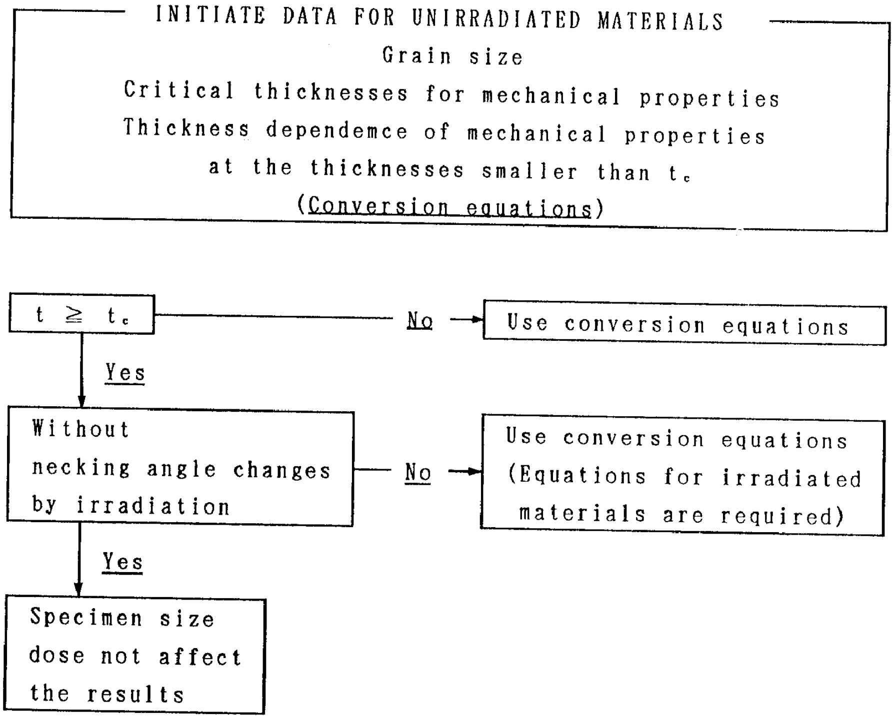

Fig. 8. Procedure to consider specimen size effects for neutron irradiated materials.

(4) Procedure to consider specimen size effects

A procedure to consider specimen size effects for neutron irradiated materials is proposed as shown in fig.8.

The first stage is to obtain basic data for unirradiated materials, such as grain size, critical thickness or aspect ratios for specific mechanical properties, and thickness dependence of mechanical properties at thicknesses smaller than t_c. Then the process along the flow chart given in fig.8 is practiced. To implement this, we have to accumulate a significant amount of data for evaluating the mechanical properties of irradiated materials. This kind of effort should be completed.

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