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# SPECIMEN SIZE EFFECTS ON D-T NEUTRON-IRRADIATED METALS[+]

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## Abstract

The specimen size effects were investigated on small sized tensile specimens of D-T neutron-irradiated Au, Cu, Ni and Fe. The size effects depend on the irradiation dose and type of metal. The mechanical properties relevant to small deformation such as yield stress can be obtained from small specimens, however, the other parameters for larger deformation amounts, viz., tensile strength and uniform elongation limit, strongly depend on the specimen size factors. The difference of size effects observed for various irradiation doses were discussed from a simple scheme. It was concluded that the prediction of size effects in highly irradiated materials is difficult from the data obtained from nonirradiated specimens.

## 1. Introduction

For the research of fission and fusion reactor materials, various types of miniaturized mechanical tests have been developed[1,2]. Among them, as a standard mechanical test, the miniaturized tensile test technique has been employed by researchers relevant to the fusion reactor materials program. In Japan, a miniaturized specimen 12.5mm in length, 2.3mm in width with a gauge section of 5.5mm × 1.2mm is widely utilized[3]. The volume of this specimen is smaller (much smaller than 1/1000) than that of the smallest specimens of conventional tensile specimens.

By using the miniaturized specimen, a large number of specimens can be irradiated at once in spite of a very small irradiation volume at a high flux density region in a testing reactor. In case of D-T neutron irradiation with such as RTNS-II (Rotating Target Neutron Source, Lawrence Livermore National Laboratory) in which the neutron flux density gradient is large due to its smallness of neutron source (diameter is smaller than 10 mm), the utilization of small specimens also provides us with specimens irradiated with

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widely varying neutron fluence levels of more than 2-orders only by one irradiation run and this promises the acquisition of accurate experimental results.

This specimen also is very convenient for direct observation of deformation structure development after applying a designed amount of deformation[4,5,6], because no especial preparatory procedures that may bring about mechanical damage such as the specimen slicing process would be neccessary.

Though the miniaturized test techniques are essentially required for fusion reactor material research with a great advantage, scaling down in specimen sizes causes several problems, viz., special care in specimen preparation and handling, matching with testing machine, specimen size effects on material properties and so on. Above all, the specimen size effect is the most important problem in the analysis of the mechanical property of the material. In the present work, the specimen size effect was investigated for Au, Cu, Ni and Fe specimens irradiated with D-T neutrons.

## 2. Experimentals

### 2.1 Specimens

Two series of specimens were prepared from pure (99.99% purity) Au, Cu, Ni and Fe in order to investigate the thickness effect and size effect.

(1) Miniaturized specimens of various thickness (TN-type)

The specimens were prepared by punching from cold-rolled sheets 0.05, 0.1, 0.2, 0.4 and 0.6 mm in thickness. The shape of the miniaturized specimens is shown in Fig. 1.

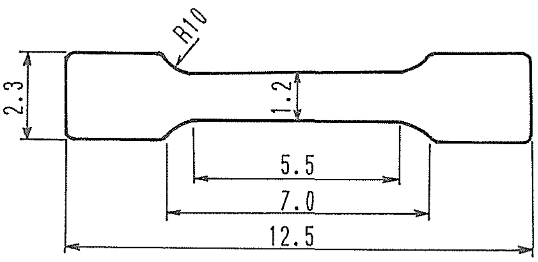

**Fig. 1** Miniaturized tensile specimen.

(2) Double and triple-sized specimens (2TN-and 3TN-type)

The specimens with double and triple sizes in all dimensions of the TN-type specimen (0.2mm thick) were also prepared. In such a manner that the specimen volume of 2TN and 3TN-type specimens is 8 and 27 times larger than TN-type specimen, respectively.

After punching, each of them was annealed at suitable temperatures, respectively, for obtaining equal grain size for specimens with different thickness in each metal. The grain sizes are about 80 $\mu$m in Au and Cu, and about 40 $\mu$m in Ni and Fe.

### 2 . 2 D-T neutron irradiation

Specimens were irradiated with 14 MeV D-T neutrons from RTNS-II. The irradiation was carried out at ambient temperature by systematic arrangement of the specimens at locations with various neutron flux density. The highest neutron fluence was $7\times10^{21}$ n/m$^2$.

### 2 . 3 Tensile test

Tensile tests were performed with Instron-type testing machine at 300K, at a strain rate $5\times10^{-4}$/s by selecting cross-head speeds corresponding to specimen size.

## 3. Experimental Results and Discussion

### 3 . 1 Yield stress

As seen in Fig. 2, thickness effect in nonirradiated TN-type specimens of Fe is almost absent. On the other hand, though the size effect on the yield stress of both nonirradiated and irradiated TN-type specimens is obvious and the yield stress of irradiated specimens increases with the increase in thickness, however their fluence dependence among irradiated specimens is small in Fe. The yield stress of double- and triple-sized Fe specimens is almost

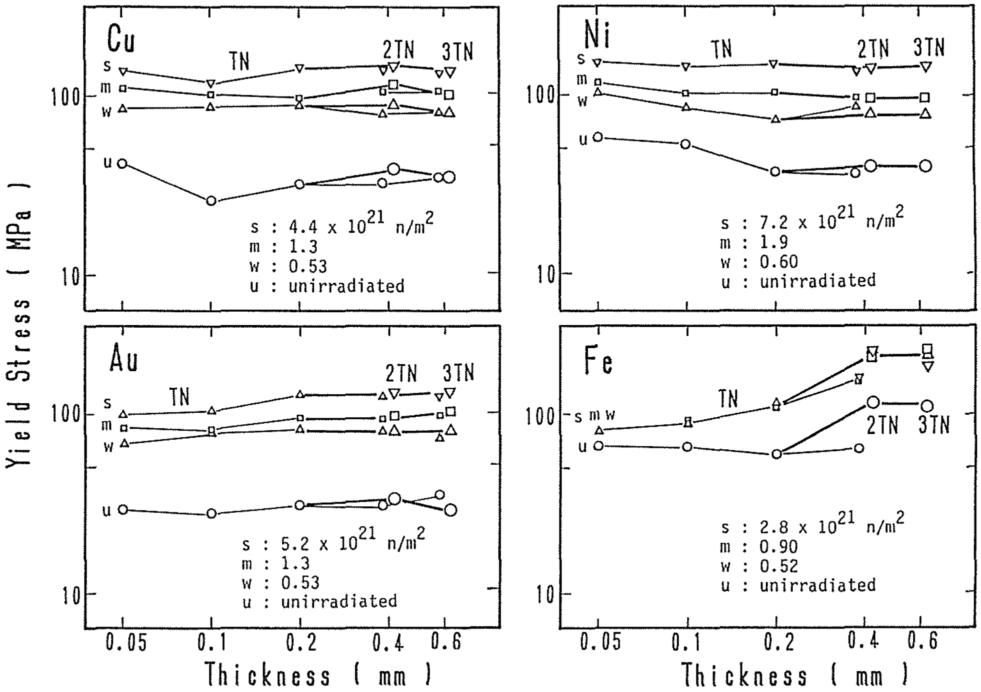

**Fig. 2** Thickness effect and size effect on yjeld stress.
Thin lines with smaller symbols; TN-type specimens.
Bold lines with larger symbols; 2TN and 3TN-type specimens.

the same. In other three kinds of metals, Au, Cu and Ni, the size effect and thickness effect for both nonirradiated and irradiated specimens can be barely observed. This suggests that the application of TN-type specimens is sufficient for the evaluation of yield stress.

### 3 . 2 Uniform elongation limit

The specimen thickness- and size-effects on the elongation are shown in Fig. 3. In Fe, no size effect and thickness effect on the uniform elongation limit are observed for non-irradiated specimens, however, the elongation limit decreases with increase in specimen size in irradiated specimens. This suggests that the locally concentrated deformation tends to take place more easily in larger specimens. The thickness effect in Fe is smaller than other metals.

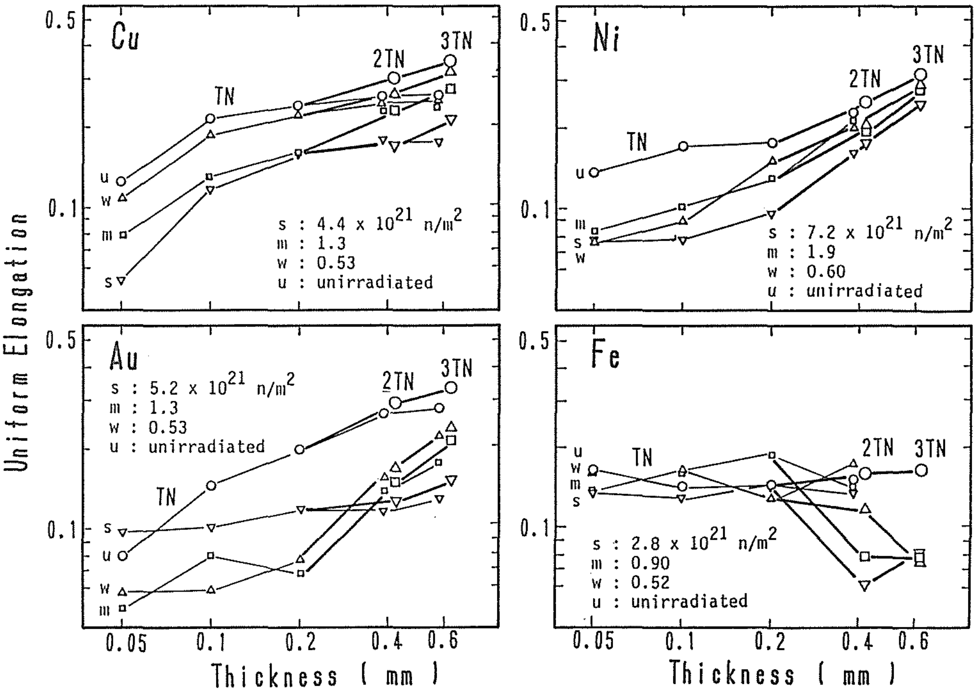

**Fig. 3** Thickness effect and size effect on the uniform elongation limit.

In Au, Cu and Ni, the uniform elongation limit increases with both thickness and specimen size. Plots for 2TN and 3TN-type specimens fall on the lines drawn for the plots of TN-type specimens. Except for Au, the decrease in the uniform elongation with fluence almost does not depend on specimen size and thickness. Au specimens irradiated to more than $5.2 \times 10^{21}$ n/m$^2$ show a smaller size effect and thickness effect. This is discussed in 3. 4.

### 3 . 3 Ultimate tensile strength

In the present work, we apply a true stress measure to the ultimate tensile strength,

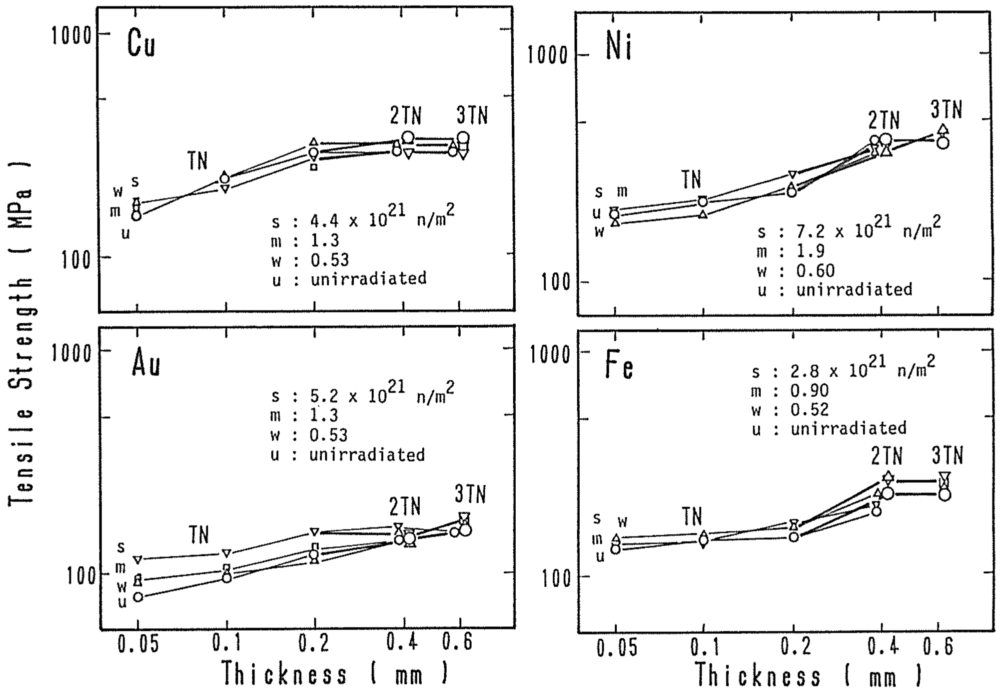

**Fig. 4** Thickness effect and size effects on the ultimate tensile strength. Stress is shown in true stress measure.

because nominal stress exhibits only the apparent strength which may give rise to misunderstanding. This parameter depends on the uniform elongation limit$^{6)}$, hence the strength may increase with the increase in uniform elongation. Their correlation can be seen by comparing Fig. 3 and 4. The ultimate strength does not depend on the irradiation fluence except for the case of Au irradiated to the highest fluence in the figure which is an exception. This is resulted from the same reason as mentioned in the preceding section.

The ultimate strength of thicker and larger Fe specimens are higher cannot be discussed in detail at present, however, the surface dislocation source may play a major role in the irradiated specimens.

### 3.4 The size effects on the irradiated metals

The dependence of ultimate strength and uniform elongation limit on thickness and the degree of irradiation hardening can be discussed by assuming the model as illustrated in Fig. 5$^{6)}$. Where, the ultimate strength of the unirradiated specimens, $\sigma_{max}$, is considered to depend on specimen thickness, t, as is shown in Fig. 5 (a).

### (a) Uniform elongation

If the yield stress of the irradiated specimen, $\sigma_y$ is lower than $\sigma_{max}$, the uniform elongation limit may be controlled by $\sigma_{max}$, viz., the uniform elongation is limited by the saturation of the work hardening in the tensile deformation. In these specimens, their flow

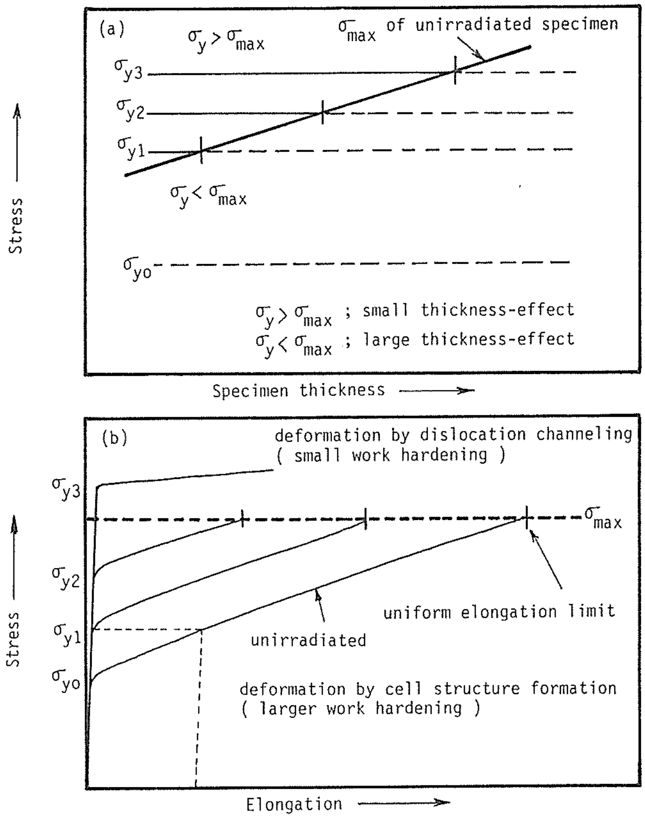

**Fig. 5** Scheme of the change in stress-strain curves for irradiated metals.
(a) Ultimate tensile strength of specimens with various thickness.
(b) Stress-strain curves for specimens irradiated to various fluence levels.
$\sigma_{max}$ ; ultimate strength, $\sigma_y$ ; yield stress.

stress may increase up to $\sigma_{max}$ with deformation amount by work hardening through the development of cell structures, even though the specimen is deformed by dislocation channeling in the early stage of deformation[4,6].

When the yield stress of irradiated material is sufficiently high to exceed the ultimate strength, $\sigma_{max}$, no work hardening can be expected[6].

In such a case, the material is deformed by dislocation channeling throughout the whole deformation process until the specimen breaks. The dislocation channeling is seen when a highly locallized slip process takes place in material containing a large number of defect clusters. In this deformation process, the variation in the flow stress is completely different from the deformation by cell structure development.

The difference in irradiation effect in specimens irradiated to higher degree or lower degree than the critical fluence, can be seen where this fluence causes the yield stress to increase to the magnitude equal to the ultimate strength of nonirradiated specimen. This is well demonstrated in the present experimental results as shown in Fig. 3, where size and thickness effects in Au are very small for the plots for the specimens irradiated to the highest fluence.

### (b) Tensile strength

In the specimens in which radiation hardening effect is still smaller even for the maximum fluence in the present experiment, viz., Cu, Ni and Fe, the ultimate tensile strength of irradiated specimens is nearly equal to that of nonirradiated specimens as seen in Fig. 4. On the other hand, the plots for Au in Fig. 4 show that the fluence dependence of tensile strength decreases with specimen thickness. This can be also explained by using the model discussed in this section.

## 3.5 Surface patterns of deformed specimens

Several examples of specimen surfaces after testing are shown in Fig. 6. The surface patterns are the same as the specimens with equal thickness, even for different type of specimens, viz., TN, 2TN and 3TN-type specimens. The surface roughness is smaller and the width of the necked portion which is smaller in thinner specimens of TN-type series. The difference in the surface roughness by the irradiation fluence is not found. The correlation between the surface deformation structure and the mechanical property change is complex.

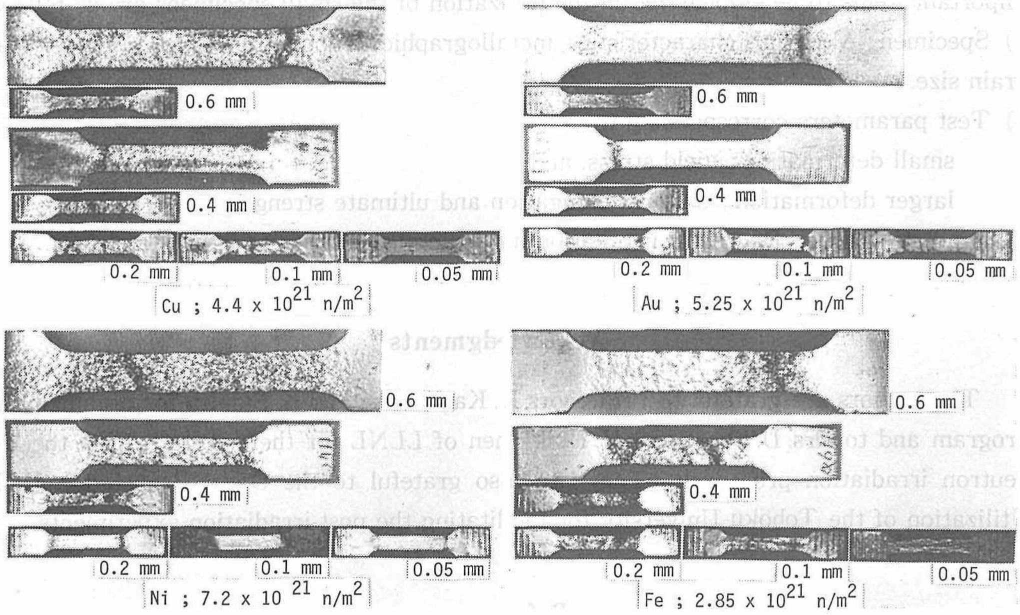

**Fig. 6** Specimen surface patterns after tensile tests. TN, 2TN and 3TN-type spemimens.

## 4. Summary

The specimen size effects on the mechanical property of D-T neutron-irradiated, Au, Cu, Ni and Fe, were investigated.

In the present work, though the irradiation fluence was much lower than those expected for the actual case of the reactor materials, the size effects was observed clearly and they were different from metal to metal. The size effects on the strength and uniform elongation limit in D-T neutron-irradiated metals were discussed from the simple scheme and the deformation mode transition.

The mechanical properties relevant to small deformation such as yield stress can be directly evaluated from small specimen data, however, the other parameters for larger deformation amounts, viz., tensile strength, uniform elongation limit, strain hardening exponent and so on, depend on the various factors. It is difficult to predict the size effects in highly irradiated materials from the data obtained from nonirradiated specimens. The important items to be emphasized in the utilization of the small specimens are as follows.

a) Specimen ; Materials characteristics, metallographic structure, preferred orientation and grain size.

b) Test parameters corresponding to,
    small deformation ; yield stress, and
    larger deformation ; uniform elongation and ultimate strength.

c) Irradiation dose ; Degree of irradiation hardening (sensitivity to irradiation).

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