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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	35
number	2
page range	171-179
year	1991-03-05
URL	http://hdl.handle.net/10097/28335

Mechanical Property and Microstructure in Neutron Irradiated Fe-Cr-Mn-Al Alloys

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(Received January 26, 1991)

Synopsis

A series of Fe-xCr-yMn-zAl alloys have been examined by tensile test and electron microscopy following irradiation in JMTR to 5 x 10^{22} n/m^2 at about 470 K. After the irradiation, 0.2% proof stress, ultimate tensile stress and total elongation were compared with the unirradiated data. From this experiment, it can be assumed that appropriate composition in these alloys is as follows: Fe-10Cr-(20-25)Mn-3Al for ferritic alloys, and Fe-10Cr-30Mn for austenitic alloys.

I. Introduction

Cr-Mn steels are candidate materials for first wall of fusion reactor applications based on low induced activity comparing to 316 austenitic steels which contained Ni [1,2]. However, recent results have indicated that neutron irradiation at high temperature for Cr-Mn steels leads to degradation of mechanical properties, phase instability and Mn loss from the surface [3-6]. Commercial Cr-Mn steels which have been used for low temperature structural materials have been examined by neutron or other charged particles irradiations [4]. Main results from these steels showed they need some improvements on oxidation resistance, mechanical properties, phase instability and neutron-irradiation properties. In order to obtain better understanding of the case of property degradation and to identify most

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promising alloy compositions, it is necessary to clarify the effects of neutron damage on mechanical properties and composition, especially on strength, elongation, phase instability and defect formation.

The aim of this study is to find optimum composition for mechanical properties of austenitic and ferritic Fe-Cr-Mn alloys following irradiation in Japan Materials Testing Reactor (JMTR), and to clarify the effect of alloying elements on mechanical properties and microstructures. In this report, a part of result from the condition at low neutron dose is discussed.

II. Experimental Procedure

Twenty-four alloys were examined in this study, which were categorized into two types; ferritic steels (8-11Cr, 5-25Mn, 0-7Al) and austenitic steels (3-10Cr, 30-40Mn). Specimen dimensions are 4mm x 16mm x 0.2mm (FFTF type) and 0.2mm x 3mm dia., for tensile test and electron microscopic observation, respectively. After cold working, these specimens were solution-annealed 1323 K for 30 min in evacuated quartz capsules and radiation-cooled. Specimens had been irradiated in He filled Al capsule. Irradiation was performed in JMTR, and the temperature was estimated at 470 K, and the fluence was 5×10^{22} n/m^2.

Following irradiation, three specimens of each alloys were assigned for tensile test at room temperature, in which the strain rate was 1.4×10^{-3} s^{-1}. Electropolishing for TEM specimens were made by a convention method with an electrolyte solution of 5% $HClO_4$ in CH_3COOH. Microstructural examinations were performed in a 200 keV TEM.

III. Result and Discussion

1. Mechanical properties of un-irradiated steels

Al addition has been tried to improve materials properties, for example, oxidation resistance, and Al added alloys showed single phase of ferrite or complex phases of ferrite and austenite, because Al is an element of ferrite former. In this study those alloys which includes ferrite phase are called as ferritic alloys.

Figure 1 shows mechanical properties of ferritic alloys before irradiation, as a function of Al content. In low Mn alloys (10Cr-5Mn), Al addition improved the total elongation, but in high Mn alloys (10Cr-25Mn) the elongation was decreased with Al content. From other properties, such as 0.2% proof stress ($\sigma_{0.2}$) and ultimate tensile

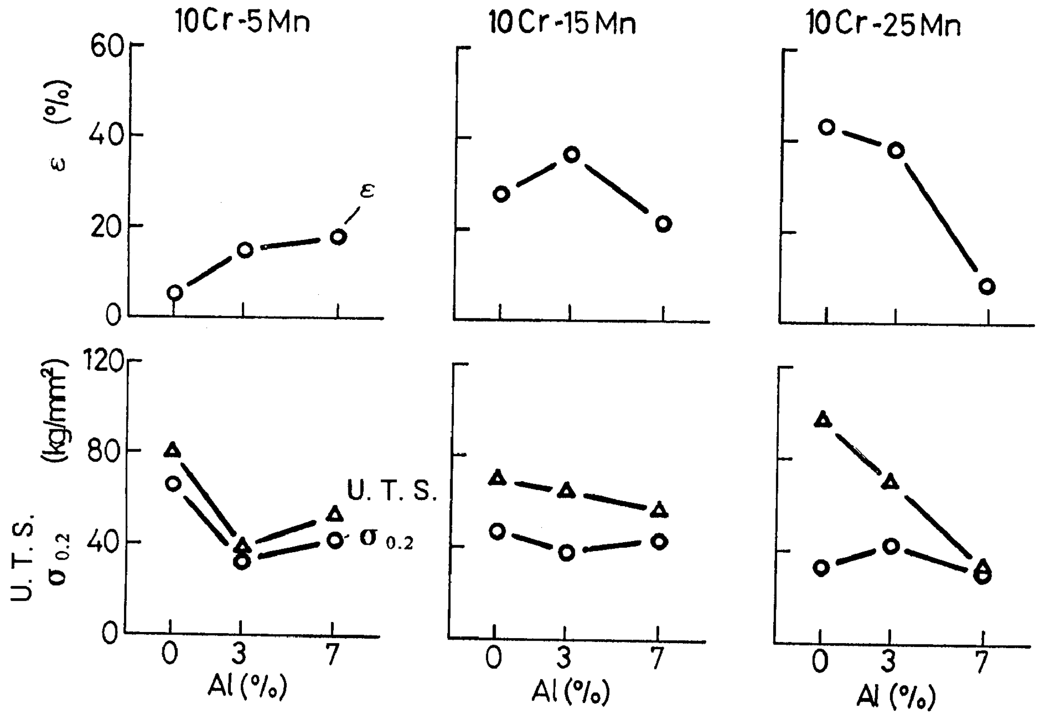

Figure 1. Mechanical property change in ferritic Fe-Cr-Mn-Al alloys before irradiation.

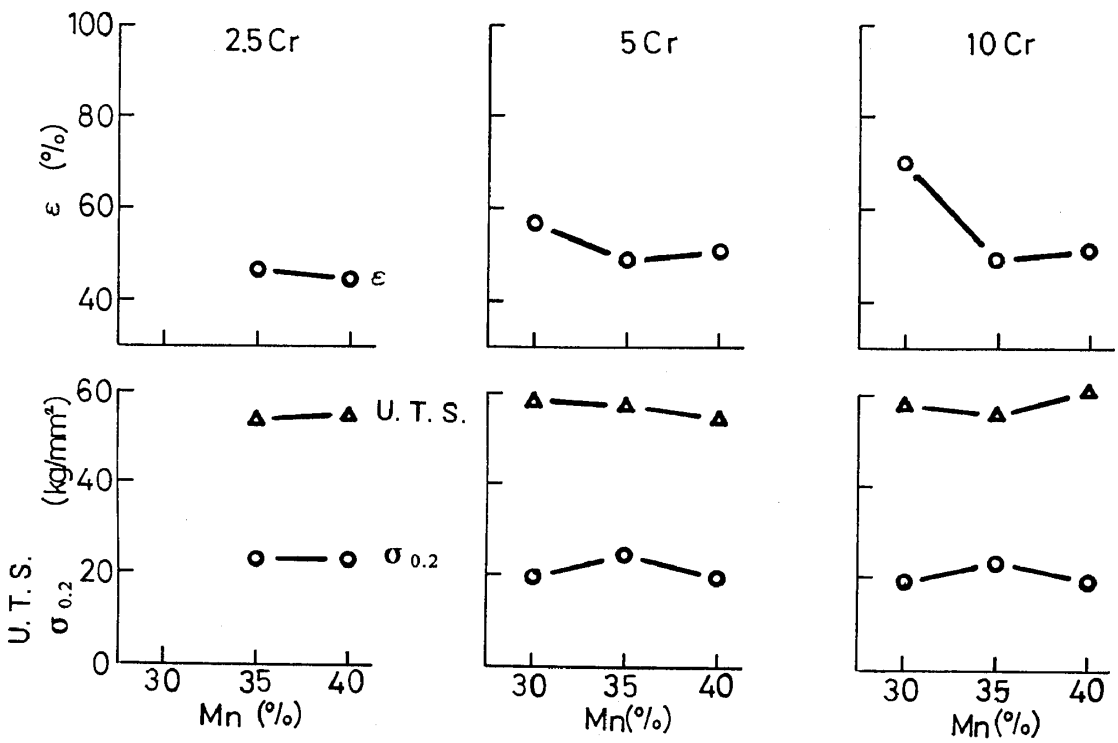

Figure 2. Mechanical property change in austenitic Fe-Cr-Mn alloys before irradiation.

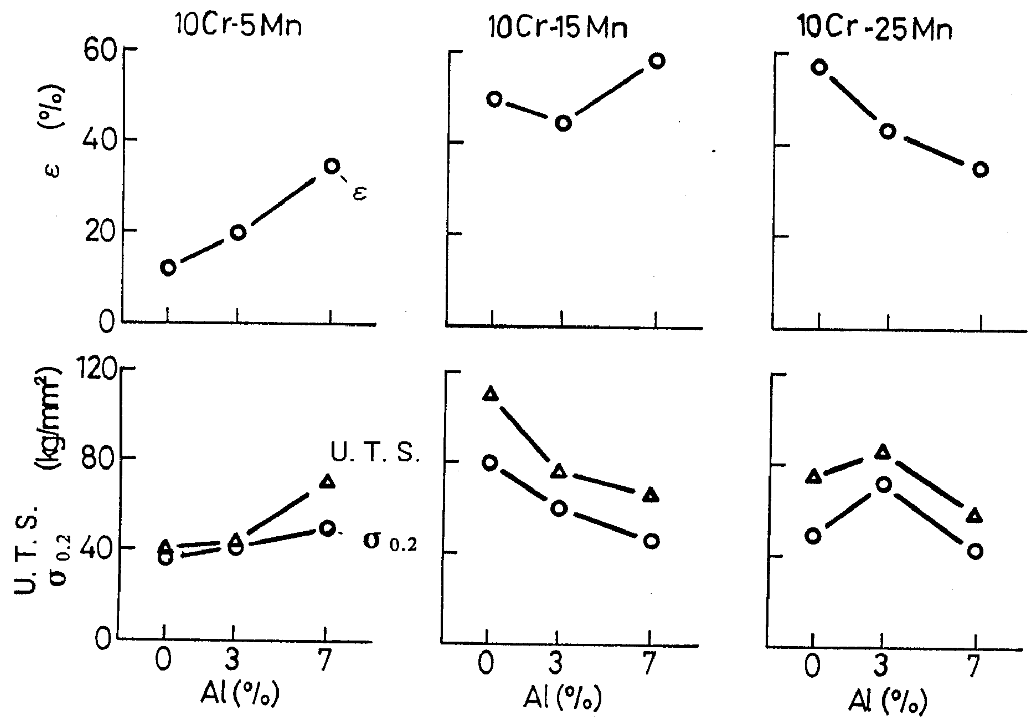

Figure 3. Mechanical property change in ferritic Fe-Cr-Mn-Al alloys after irradiation.

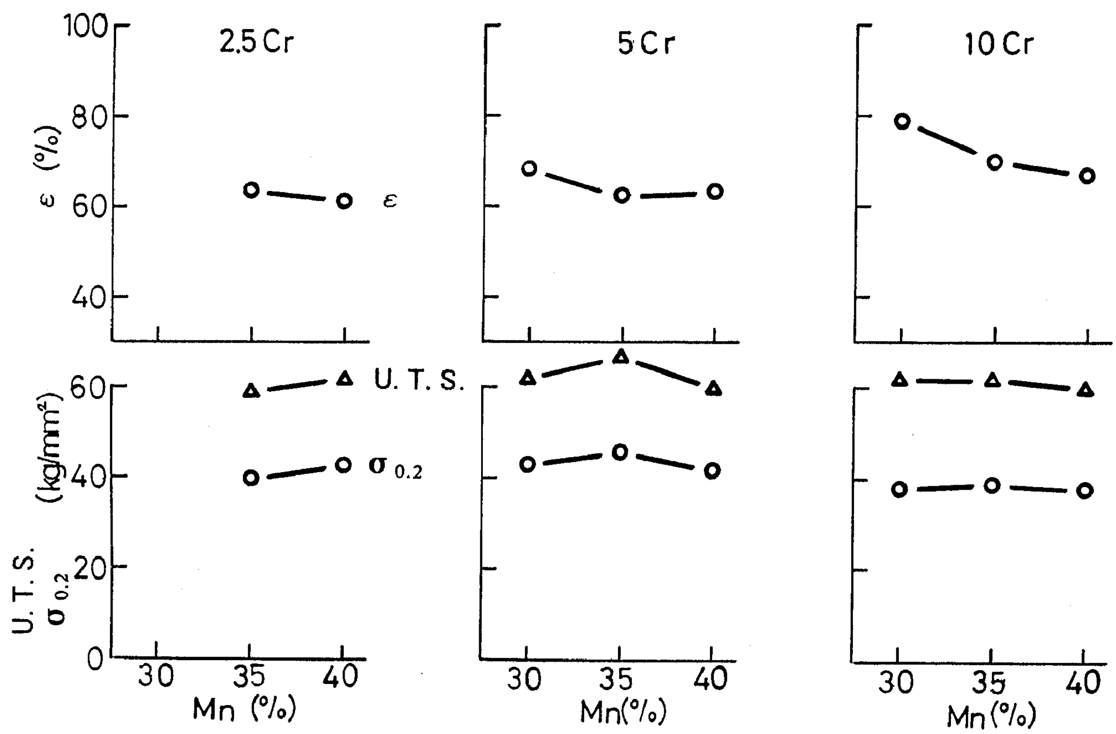

Figure 4. Mechanical property change in austenitic Fe-Cr-Mn alloys after irradiation.

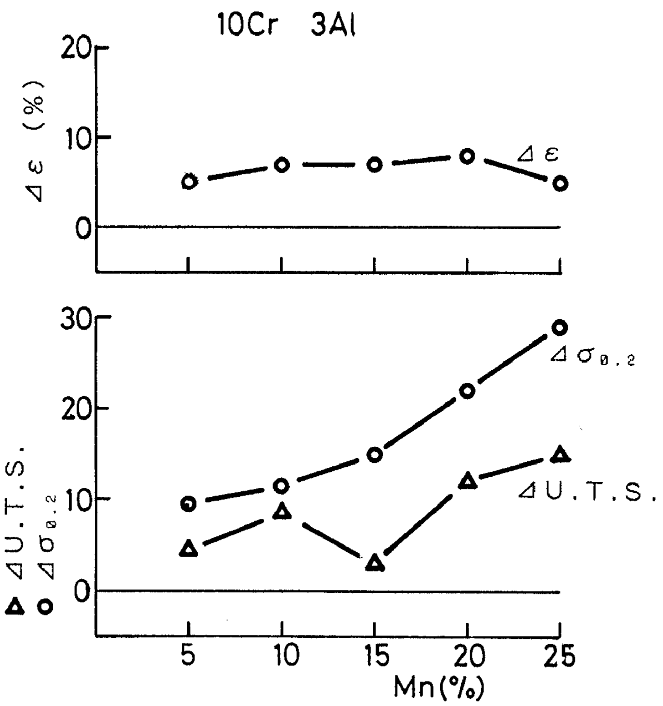

Figure 5. Difference in mechanical properties of ferritic Fe-Cr-Mn-Al alloys after and before irradiation.

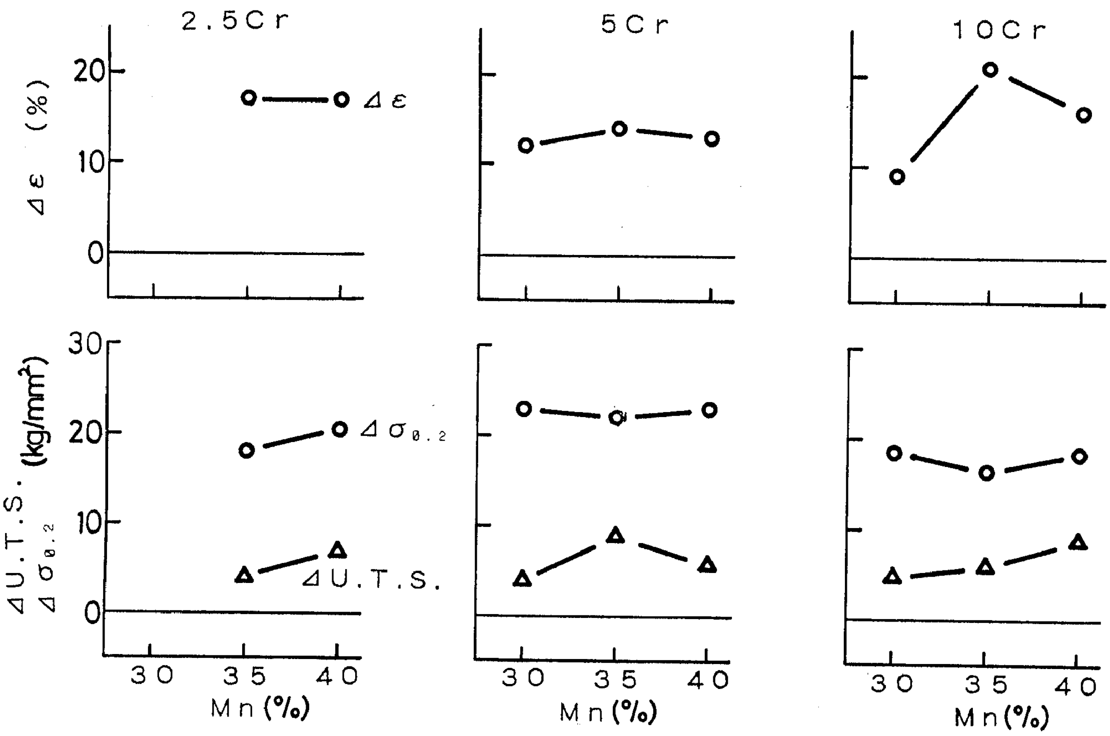

Figure 6. Difference in mechanical properties of ferritic Fe-Cr-Mn alloys after and before irradiation.

stress (UTS), the optimum composition in ferritic alloys which contained Al can be assumed to be 10Cr-15Mn-3Al.

Figure 2 shows mechanical properties in austenitic Fe-Cr-Mn alloys before irradiation. In these alloys except 10Cr, mechanical properties didn't show drastic changes with Cr and Mn contents. Therefore, to consider oxidation resistance the appropriate composition should be around 10Cr-30Mn.

2. Mechanical properties of irradiated steels

Figure 3 shows mechanical properties in ferritic Cr-Mn-Al steels after irradiation. In alloys without Al, 10Cr-15Mn and 10Cr-25Mn had good properties. In alloys which included Al, as same as unirradiated condition, the mechanical properties were improved by Al addition up to 3 %, and the elongation decreased strongly at 10Cr-25Mn-7Al. Therefore, appropriate alloys which have good properties after this irradiation were 10Cr-15Mn-3Al or 10Cr-25Mn-3Al.

Figure 4 shows mechanical properties in irradiated austenitic alloys. In some 10Cr alloys, the elongation was reduced with increasing Mn content. However, mechanical properties did not show clear temperature dependence in other alloys. Therefore, 10Cr-30Mn alloy had good mechanical properties.

Both of these alloys didn't show big changes in mechanical properties. To consider the irradiation effect on mechanical properties, the difference was defined as follows:

$$\Delta\sigma_{0.2} = \sigma_{0.2}(\text{irradiated}) - \sigma_{0.2}(\text{unirradiated})$$

$$\Delta e = e\,(\text{irradiated}) - e\,(\text{unirradiated})$$

$$\Delta\sigma\,\text{UTS} = \sigma\,\text{UTS}\,(\text{irradiated}) - \sigma\,\text{UTS}\,(\text{unirradiated})$$

In these $\sigma_{0.2}$ has been well-known as irradiation-hardening.

Figure 5 shows the difference in mechanical properties of ferritic alloys between after and before irradiation. It can be noted that all of parameters of mechanical properties,i.e. proof stress, UTS and elongation, had positive values. With increasing of Mn content, proof stress and UTS were increased, but the elongation had an almost constant value of about 5 %.

Figure 6 shows the difference of mechanical properties in austenitic alloys. All of parameters increased, but were almost constant with changing of Mn content, where the irradiation produced the elongation of the values with 10 - 20 %. Other irradiation studies have shown such small amount of irradiation can induce the increment of proof stress and the decrease of elongation, therefore, the increase of elongation after irradiation should be remarkable in this study.

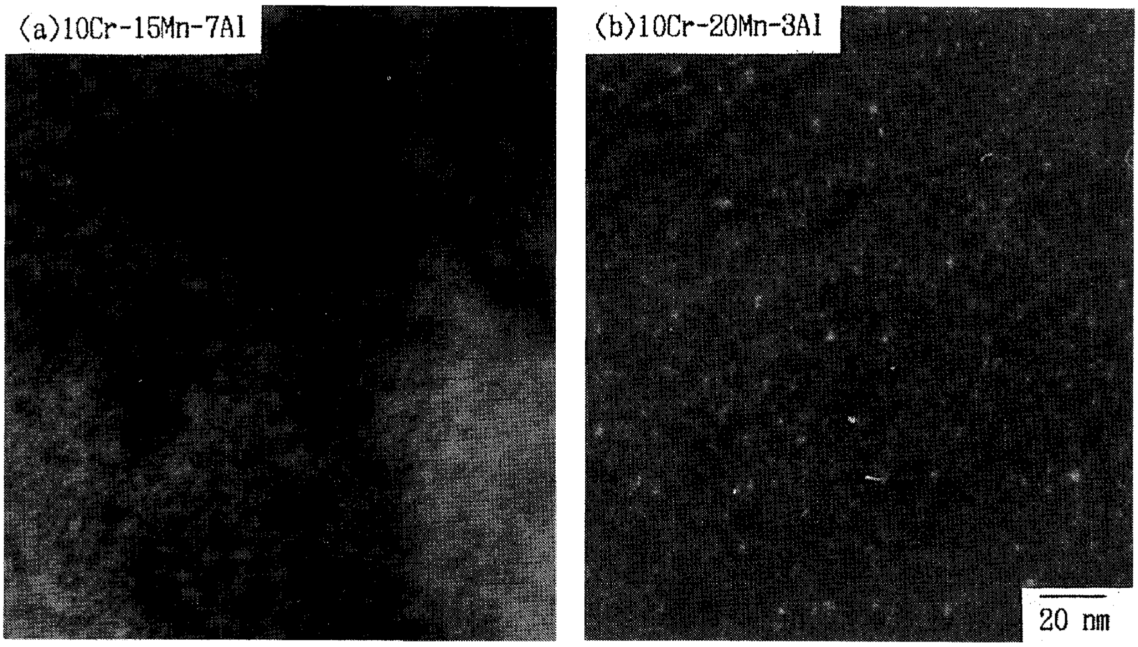

Figure 7. Dark field images of fine defect-clusters in ferritic 10Cr-15Mn-7Al (a) and 10Cr-20Mn-3Al (b) alloys after irradiation.

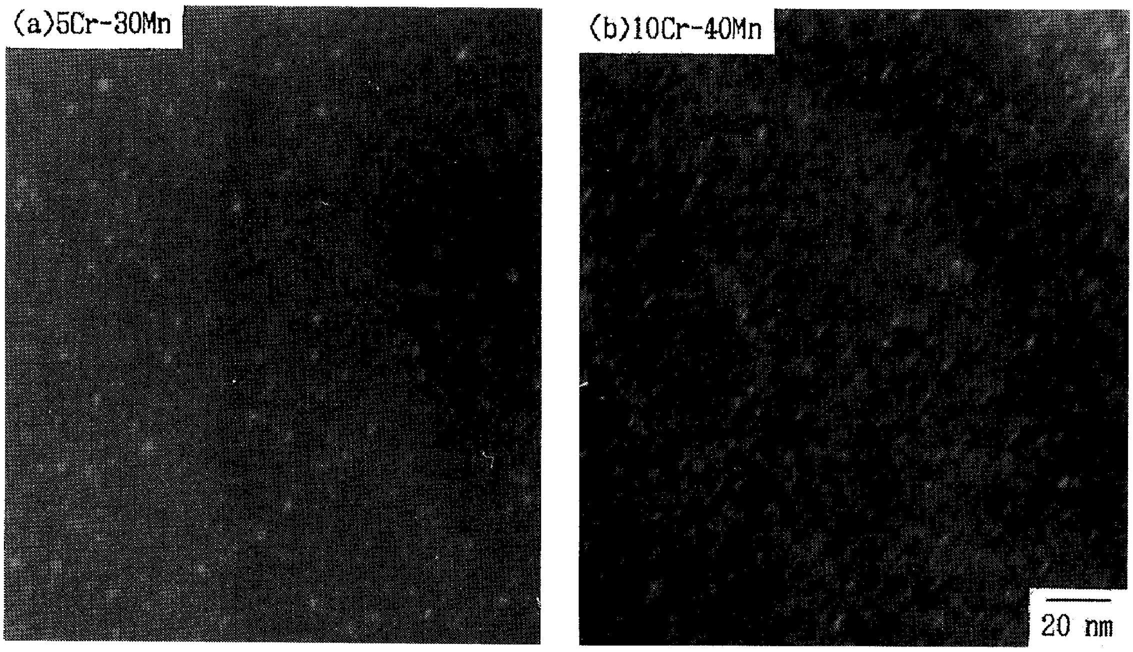

Figure 8. Dark field images of fine defect-clusters in austenitic 5Cr-30Mn (a) and 10Cr-40Mn (b) alloys after irradiation.

3. Microstructural change

To understand these changes after irradiation, TEM observation has carried out in typical irradiated alloys. As this irradiation condition was at low neutron dose and low temperature, no obvious change can be observed in structures of grain boundaries and precipitates, but in almost all of alloys fine defect-clusters of 1 - 5 nm in diameter were produced homogeneously. Figure 7 shows dark field images of fine defect-clusters in ferritic alloys, where thickness of the observed area was about 40 nm. In 10Cr-15Mn-7Al (a) which showed no large change in proof stress after the irradiation, no clear defect-clusters were observable. On the contrary, in 10Cr-20Mn-3Al (b) which had large change in proof stress, there were lots of defect-clusters. From this result the suppression of defect cluster could be explained by the addition of Al which can trap point defects and enhances the mutual recombination.

Figure 8 is dark field images from austenitic 5Cr-30 Mn (a) and 10Cr-40Mn (b) which had almost same values in increment of proof stress after irradiation. In both of alloys defect-clusters were formed with almost same in size and number density. From the comparison between the proof stress and microstructural changes, the increase of proof stress in irradiation alloys can be explained qualitatively as that the fine defect clusters disturb the dislocation motion [7]. However, it has not been explained that what does cause the increasing of elongation after this irradiation. It should be a next subject to study in near future.

IV. SUMMARY

Twenty-four alloys of Fe-xCr-yMn-zAl system have been examined by tensile test and electron microscopy following irradiation in JMTR to 5 x 10^{22} n/m^2 at about 470 K, and compared with the unirradiated data.

(1) 0.2% proof stress was increased by the irradiation, and the increment was different in alloy systems: it increased with Mn content in ferritic alloys, and had no dependence with Mn and Cr contents.

(2) From TEM observation the increase of proof stress is caused by fine defect-clusters formed during irradiation. However, the increase in total elongation cannot be explained in this study.

(3) From the comparison between unirradiated and irradiated alloys, it can be concluded that appropriate composition which shows good mechanical properties, is as follows: Fe-10Cr-(20-25)Mn-3Al for

ferritic alloys, and Fe-10Cr-30Mn for austenitic alloys.

ACKNOWLEDGMENT

The authors wish to acknowledge to Prof. H. Kayano for excellent management, and to Mr. M. Narui for irradiation details. This work has been performed for one of collaboration at Oarai Branch of Tohoku University in 1990's foundation.

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