1.1 Selected Reduced Activation Ferritic-Martensitic (RAFM) Steels For HFIR Experiments JP-30/31 — L. Tan (Oak Ridge National Laboratory)

OBJECTIVE

Characterize the tensile properties and microstructure of selected RAFM steels to ensure their initial condition suitable for neutron irradiation assessment and prepare specimens for the HFIR experiments JP-30/31.

SUMMARY

Three heats of RAFM steels were selected for HFIR experiments. A modified-NF616 was also selected for comparison. Tensile tests of the heats were performed at temperatures of 23°C, 300°C, 400°C, and 650°C, which showed tensile properties comparable to the oxide dispersion strengthened (ODS) steel PM2000. Microstructural analysis indicates that fine lath boundaries with nano-precipitates had been developed in the heats by the specific thermomechanical treatment.

PROGRESS AND STATUS

Introduction

The fast decay characteristics of induced radioactivity in RAFM steels have promoted the development of this category of FM steels. The Japanese F82H and the European heat EUROFER 97 are two promising examples of RAFM steels. Recent FM steel development at ORNL showed significant strengthening capability by means of specific thermomechanical treatment (TMT) [1]. This approach is also applicable to RAFM steels, which had shown refined lath boundaries and precipitates, leading to enhanced hardness and tensile properties [2]. However, irradiation resistance of the RAFM steels needs to be assessed. Progress of the neutron irradiation experiments using HFIR at ORNL is reported here.

Heats Preparation and Evaluation

Three RAFM steels, together with a modified-NF616 steel, were selected for the HFIR experiments JP30/31. Their nominal compositions in weight percentage (wt%) are listed in Table 1. The steels were in wrought condition. To produce expected FM microstructure, specific TMTs were applied to wrought steels. The selection of normalization and tempering temperatures of the steels was guided by computational thermodynamics. Using heat 1539 as an example, Figure 1 shows the calculated phase mole fraction as a function of temperature. The heat 1539 was normalized at 1100°C for 1 h followed by tempering at 750°C and air cooling. A deformation of ~60% was applied to the heat at the normalization temperature to refine microstructure and promote precipitation.

Table 1. Nominal composition (wt%) of the heats.

Heat	Cr	Mn	V	Si	W	Ta	Mo	Nb	Ni	Cu	C	N
1537	9.0	0.5	0.3	0.25	1.1						0.02	0.06
1538	9.0	0.5	0.3	0.25	1.1	0.1					0.02	0.06
1539	9.0	0.5	0.3	0.25	1.1	0.1					0.1	0.06
Modified-NF616	8.5	0.4	0.3	0.15	2.2		0.1	0.1	0.4	0.1	0.01	0.08

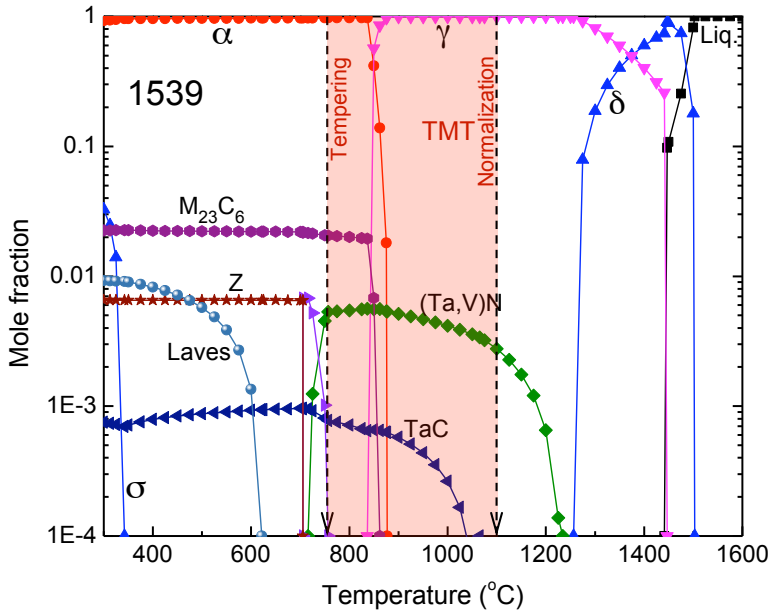

Figure 1. Example of calculated mole fraction of phases in heat 1539 as a function of temperature.

The microstructure of the processed heats was characterized by optical microscopy and transmission electron microscopy (TEM). The optical images (not shown here) showed typical FM microstructure with prior-austenite grains and dense lath packets and boundaries in the samples. Figure 2 shows the TEM images in both bright-field (BF) and dark-field (DF) mode of the heats 1538, 1539, and modified-NF616. In addition to the fine lath boundaries, many (Ta,V)N and (Nb,V)N in nanometers and Cr-rich carbides in sub-micrometers were developed in the materials. Additionally, ultra-fine nano-precipitates with a density in the order of 1022/m3 were observed in the heats 1538 and modified-NF616, as shown in their respective DF images, which may benefit irradiation resistance. The chemical composition of these ultra-fine nano-precipitates was not able to be characterized. Unlike the ultra-fine nano-precipitates primarily decorating lath boundaries as shown in the DF image of the heat 1538, the ultra-fine nano-precipitates are dispersed in the matrix of the modified-NF616.

Miniature tensile specimens (type SS-J3: 16 x 4 x 0.76 mm) were prepared from the processed heats using electric discharge machining (EDM) for tensile tests. Figure 3 shows the yield strength and total elongation of the specimens tested at 23°C, 300°C, 400°C, and 650°C that are consistent with the targeted neutron irradiation temperatures. The results of F82H [3], NF616 [4], and ODS steel PM2000 [5] are also included in Figure 3 for comparison. The samples of the RAFM heats and the modified-NF616 showed tensile properties comparable to the ODS steel PM2000 and greater strength than the F82H and NF616.

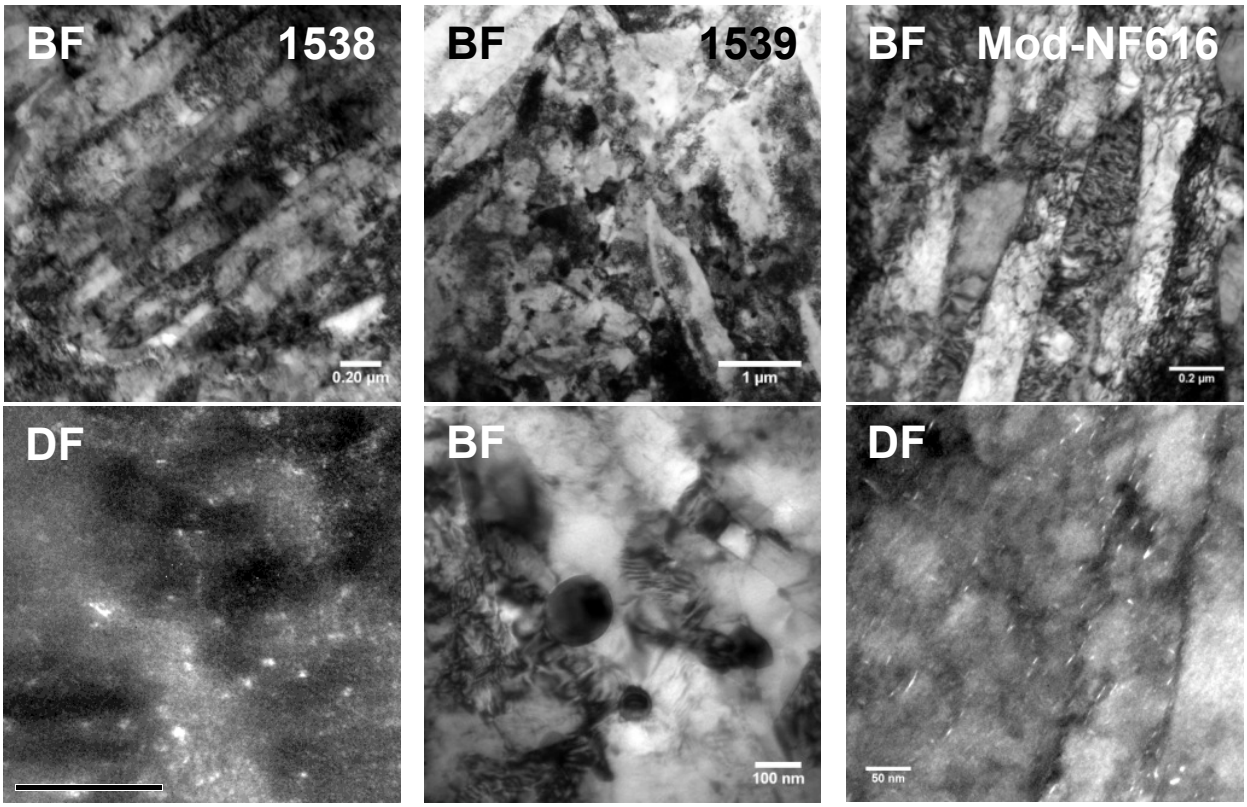

Figure 2. Bright-field (BF) and dark-field (DF) TEM images of heats 1538, 1539, and modified-NF616 at low (upper row) and high (lower row) magnifications.

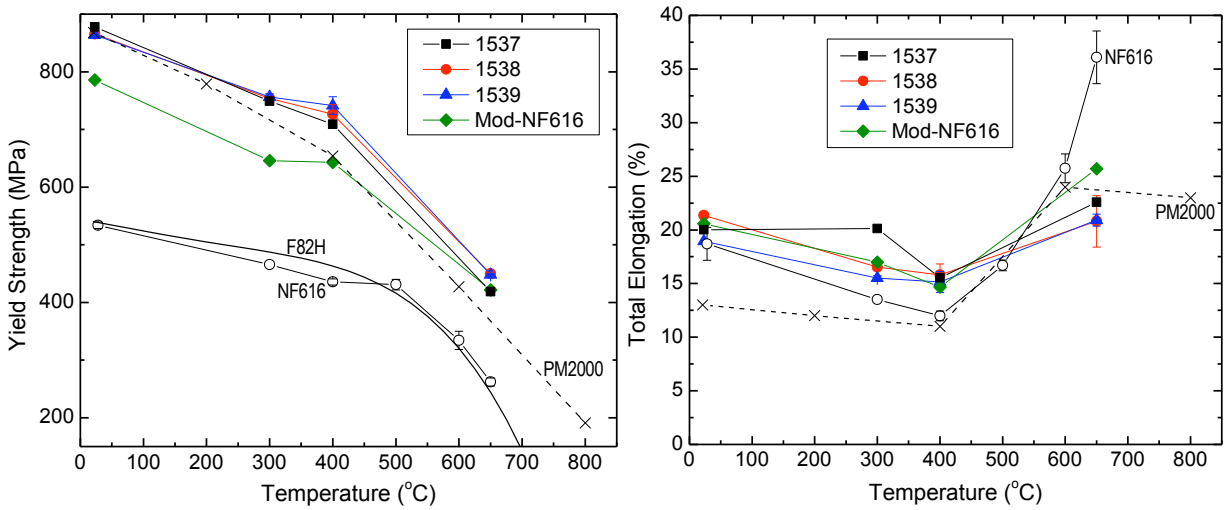

Figure 3. Yield strength and total elongation of the heats 1537, 1538, 1539, and modified-NF616.

Specimens Preparation for the HFIR Experiments JP-30/31

Four types of specimens were prepared for the HFIR experiments JP-30/31 using EDM. They are type SS-J3 miniature tensile specimens, 3-notch or 5 notch bend bars (M3PCCVN 36 x 3.3 x 1.65 mm and M5PCCVN 54 x 3.3 x 1.65 mm), specimens for preparing atom probe samples (APFIM 16 x 1.14 x 0.5 mm), and TEM disks (∅3 x 0.25 mm). The numbers of the specimens for the four heats (1537, 1538, 1539, and modified-NF616) are listed in Table 2.

Table 2. Specimens prepared for the HFIR experiments JP-30/31.

JP30/31	Specimen Type	Heat 1539	1538	1537	Mod-NF616	Total Number
300°C	SS-J3	4	3	3		10
	M3PCCVN	3	3	3		9
	APFIM	1	1	1	1	4
	TEM disk	3	3	3	3	12
400°C	SS-J3	3	3	2		8
	M5PCCVN	2				2
	APFIM	1	1	1	1	4
	TEM disk	3	3	3	3	12
650°C	SS-J3	2	2	2		6
	M5PCCVN	2				2
	APFIM	1	1	1	1	4
	TEM disk	3	3	3	3	12

REFERENCES

[1] R. L. Klueh, N. Hashimoto, P. J. Maziasz, *Scripta Mater.* **53** (2005) 275-280.
[2] L. Tan, D. T. Hoelzer, J. T. Busby, M. A. Sokolov, R. L. Klueh, submitted to *J. Nucl. Mater.* 2011.
[3] S. J. Zinkle, J. P. Robertson, R. L. Klueh, Fusion Materials - Semiannual Progress Report for Period Ending June 30, 1998 (DOE/ER-0313/24), pp. 135-143.
[4] L. Tan, J. T. Busby, P. J. Maziasz, Y. Yamamoto, submitted to *J. Nucl. Mater.* 2011.
[5] R. L. Klueh, J. P. Shingledecker, R. W. Swindeman, D. T. Hoelzer, *J. Nucl. Mater.* **341** (2005) 103-114.