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Elastic Modulus Measurement of ORNL ATF FeCrAl Alloys

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OAK RIDGE NATIONAL LABORATORY
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Fuel Cycle Research and Development

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ABSTRACT

Elastic modulus and Poisson's ratio for a number of wrought FeCrAl alloys, intended for accident tolerant fuel cladding application, are determined via resonant ultrasonic spectroscopy. The results are reported as a function of temperature from room temperature to 850°C. The wrought alloys were in the fully annealed and unirradiated state. The elastic modulus for the wrought FeCrAl alloys is at least twice that of Zr-based alloys over the temperature range of this study. The Poisson's ratio of the alloys was 0.28 on average and increased very slightly with increasing temperature.

1. INTRODUCTION

FeCrAl alloys have been proposed as accident tolerant fuel cladding concepts to replace Zr-based alloys in light water reactors [1]. One of the aspects of the viability of these cladding materials that needs to be assessed is their thermo-mechanical performance under normal operating conditions. This assessment can be carried out effectively using fuel performance analysis codes assuming detailed and accurate temperature- and dose-dependent material property data are available. Therefore accurate material property information is necessary that needs to be obtained using well-controlled experiments on applicable materials.

One important input into fuel performance analysis tools is the elastic modulus of the cladding. This study aims to provide accurate data on the elastic modulus of FeCrAl cladding as a function of temperature. Although there is information available in the literature regarding a number of commercial alloys, this study specifically examines nuclear-grade alloys under development at ORNL [2].

2. EXPERIMENT APPROACH

Resonant ultrasound spectroscopy (RUS) [3] was used to determine, for several FeCrAl alloys, Young's modulus and Poisson's ratio as a function of temperature. The experiments were performed at room temperature and at several other temperatures up to 850°C. Additional measurements were also made as the samples cooled from 850°C to room temperature to investigate any possible effect of heating on microstructure that might lead to a change in the elastic modulus. The tests were carried out on six different alloys, produced at ORNL [2], with the compositions specified in Table 1. The alloys were all in the fully annealed condition (T<700°C).

FeCrAl alloy disk specimens, 15 mm in diameter and between 1.2 mm and 2.0 mm in height, were prepared from plates by electrical discharge machining using a Robocut α-oiA machine with a Fanuc Series 18i-W controlling unit. To remove the oxide layer and produce flat specimens, a table grinder was used to achieve flatness of ± 0.6% of the average height. This is important since a well-known and flat geometry is critical for reliable analysis of RUS data. The disks initially underwent room temperature scans on a Quasar RUSPEC. The spectra were viewed using Galaxy software and the elastic moduli were calculated from the spectrum peaks and density using CylModel v2.68b software. For high temperature testing, the RUS probes and sample were placed inside a furnace that was purged of oxygen. Ar with < 10 ppb of O_2, < 20 ppb of H_2O, < 100 ppb of THC, and < 5 ppm of N_2 was cycled through the system during testing. The furnace started at room temperature (around 22 °C) and ramped up to 50 °C at a rate of 3 °C / min. It then soaked at 50 °C for 20 min. After that, the furnace ramped up at a rate of 3 °C / min stopping every 50°C for 20 min up to 850°C. The furnace then cooled back down to room temperature at a rate of 3 °C / min stopping every 50 °C until it reached 100 °C. At this point the furnace was turned off allowing the sample in the furnace to cool down to about 60 °C and then air cool back to room temperature. Scans were taken at initial and final room temperatures and at 100 °C, 200 °C, 300 °C, …, 800 °C, and 850 °C while heating and 700 °C, 500 °C, 400 °C, 300 °C, 200 °C, and 100 °C while cooling. The scans were initiated by Universe software after 10 min once soaking began and saved by Galaxy software. Each spectrum was later fit and the elastic moduli calculated using CylModel v2.68b software.

Table 1. ORNL FeCrAl alloy composition in wt%.

Alloy ID	Fe	Cr	Al	Y	Mo	Si	Nb	C	S	O	N	P
B106Y	83.98	10.06	5.93	0.003	<0.01	<0.01	<0.01	0.0040	0.0028	0.0118	0.0015	<0.002
T35Y	82.26	13.18	4.44	0.07	<0.01	0.01	<0.01	0.0040	0.0009	0.0022	0.0026	0.009
B136Y	80.85	12.99	6.14	0.003	<0.01	<0.01	<0.01	0.0030	0.0020	0.0014	0.0005	<0.002
C35M3	79.43	13.06	5.31	0.053	2	0.13	<0.01	0.001	<0.0003	0.0012	0.0003	0.007
C36M2	78.4	13	6.29	0.059	1.99	0.2	<0.01	0.001	<0.0003	0.001	0.0004	0.004
B166Y	77.86	16.06	6.06	0.003	<0.01	<0.01	<0.01	0.0030	0.0023	0.0014	0.0004	<0.002

3. RESULTS AND DISCUSSION

Elastic moduli of the various ORNL FeCrAl alloys examined in this study are plotted in Figure 1 as a function of temperature. Also, for the sake of comparison, the elastic modulus of Zircaloy as well as two dispersion strengthened FeCrAl alloys are included in the figure. Note that the wrought FeCrAl alloys exhibit an elastic modulus 2.1× greater than Zr-based alloys at RT. This ratio monotonically increases to 2.7 at 850°C. Though some variation is observed among the data for the various wrought alloys, no significant difference between the moduli of the alloys as a function of major alloying elements (Cr and

Al) is noted. The C series alloys that contain 2wt% Mo appear to have a slightly higher elastic modulus. In any case, these small variations may be neglected and an overall polynomial fit to the modulus data as a function of temperature can be produced, as shown in Eq. (1).

$$E = -5.46\times10^{-5}T^{2} - 3.85\times10^{-2}T + 1.99\times10^{2} \quad (1)$$

where E is the elastic modulus in GPa and T is temperature in °C.

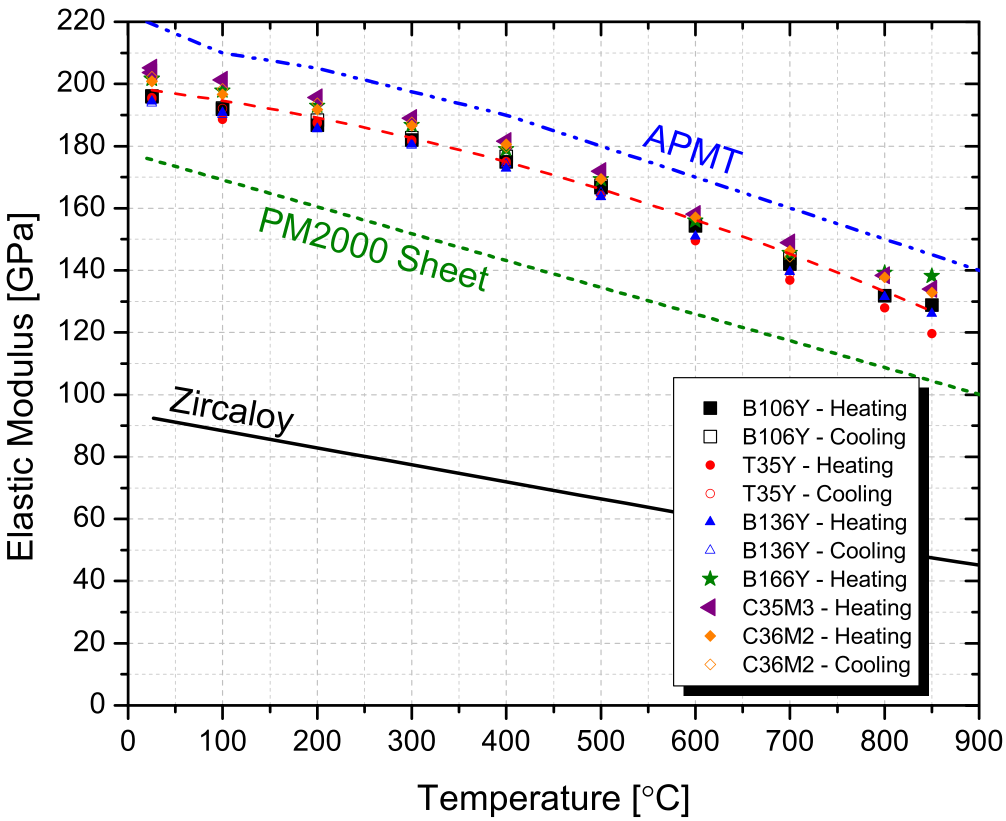

Figure 1. Elastic moduli of the various ORNL wrought FeCrAl alloys as a function of temperature, compared to Zircaloy [4], PM2000 [5], and AMPT [6].

Figure 2 shows the value of Poisson's ratio for the various ORNL wrought FeCrAl alloys as a function of temperature. Again, no major trend as a function of major alloying elements is observed in this dataset. The Poisson's ratio for all the alloys increases slightly with increasing temperature; this trend is approximated with a linear fit from room temperature to 700°C:

$$\nu = 3.85\times10^{-5}T + 2.68\times10^{-1} \quad (2)$$

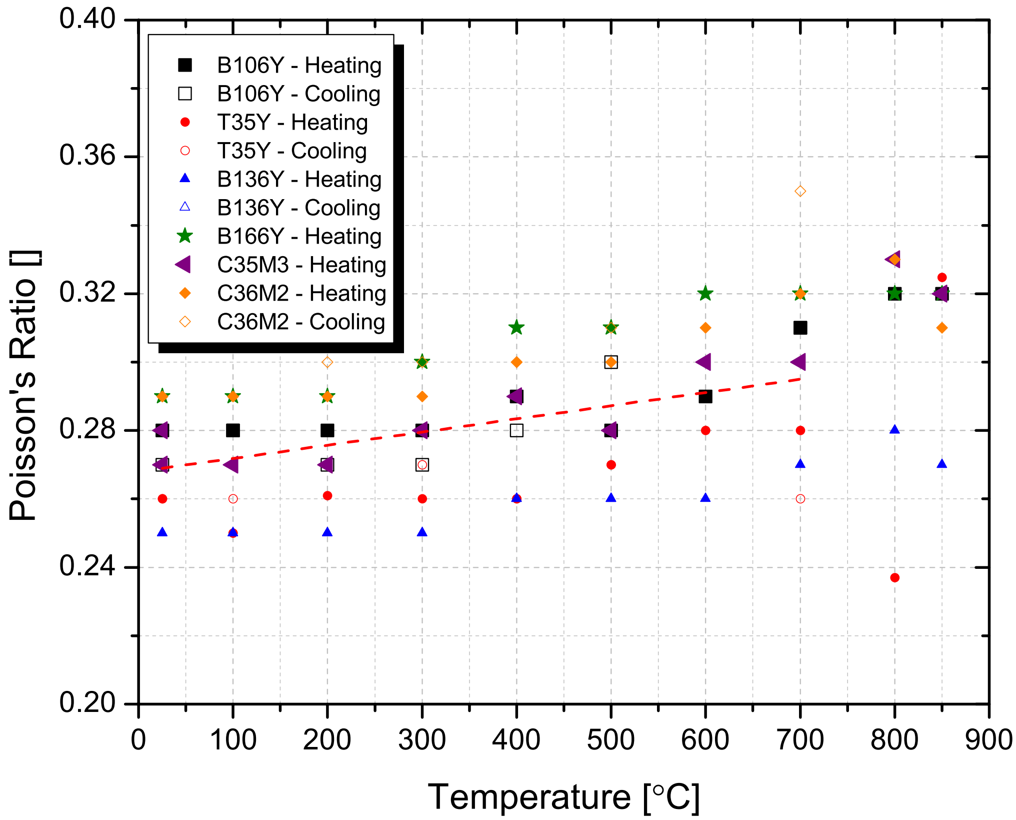

Figure 2. Poisson's ratio of the various ORNL wrought FeCrAl alloys as a function of temperature.

In case of both the elastic modulus and Poisson's ratio, very similar values are obtained during the heating and cooling curves for the various wrought FeCrAl alloys. High temperature annealing does not seem to affect the value of the Young's modulus, though this is expected since most of the alloys were fully annealed at T>700°C prior to testing.

4. SUMMARY

Resonant ultrasonic spectroscopy was used to determine the elastic modulus and Poisson's ratio for the various wrought FeCrAl alloys produced at ORNL as a function of temperature. The alloys were in the fully annealed and unirradiated state. The elastic modulus of these ferritic alloys was 2.1-2.7× larger than that of Zr-based alloys over the temperature range of this study (25-850°C). This higher modulus value will enable utilization of thinner cladding that is envisioned for FeCrAl alloys. The Poisson's ratio of the alloys increased slightly with increasing temperature over this range.

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[6] “Kanthal APM and APMT Tube Material datasheet, AB Sandvik group, Sandviken, Sweden.”

Appendix A: Measured Elastic and Shear Moduli, Poisson's Ratio, and Associated Error for Wrought ORNL FeCrAl Alloys

B106Y – Heating

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	195.85	76.68	0.28	1.5989
25	195.9	76.67	0.28	1.6203
100	191.89	75.01	0.28	1.5957
200	186.7	72.74	0.28	1.57
300	181.91	70.82	0.28	1.61
400	174.9	68.04	0.29	1.69
500	166.6	65	0.28	2.72
600	154.32	59.63	0.29	1.94
700	141.99	54.35	0.31	1.52
800	131.85	50.07	0.32	1.85
850	128.81	48.78	0.32	2.36

B106Y - Cooling

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
700	143.79	55.02	0.31	2.04
500	167.3	64.53	0.3	1.58
400	176.64	69.14	0.28	2.19
300	182.71	71.8	0.27	1.46
200	188.4	73.96	0.27	1.1
100	192.19	75.29	0.28	0.7
25	196.13	77.08	0.27	0.76

T35Y - Heating

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	195.64	77.48	0.26	2.7262
25	195.70	77.8	0.26	1.0453
100	188.57	75.17	0.25	1.3854
200	187.74	74.44	0.26	1.1225
300	182.01	72.28	0.26	1.1094
400	175.05	69.6	0.26	1.2833
500	164.13	64.84	0.27	1.2149
600	149.52	58.61	0.28	1.5751
700	136.89	53.6	0.28	1.4579
800	127.98	51.73	0.24	2.6234
850	119.68	45.17	0.32	3.4268

B136Y - Cooling

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
700	139.73	54.74	0.28	1.64
500	165.02	65.68	0.26	1.91
400	174.2	69.37	0.26	1.46
300	180.14	71.84	0.25	1.3
200	185.47	74.34	0.25	1.17
100	190.16	76.29	0.25	1.15
25	193.8	77.83	0.25	1.13

B166Y - Heating

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	201.61	78.02	0.29	1.02
25	201.6	78.02	0.29	1.5
100	197.74	76.38	0.29	0.98
200	192.88	74.48	0.29	1.02
300	186.73	71.76	0.3	1.05
400	178.92	68.55	0.31	1.17
500	169.24	64.49	0.31	1.17
600	156	59.14	0.32	1.44
700	145.52	54.96	0.32	1.46
800	139.13	52.59	0.32	2.88
850	138.09	52.46	0.32	3.3

C35M3 - Heating

Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	203.65	79.27	0.28	2.36
25	205.13	80.86	0.27	2.11
100	201.33	79.23	0.27	2.15
200	195.63	76.78	0.27	2.21
300	188.98	74	0.28	2.27
400	181.57	70.26	0.29	2.66
500	171.96	67.06	0.28	2.41
600	158.15	60.65	0.3	2.92
700	148.87	57.05	0.3	3.92
800	138.32	52.06	0.33	4.83
850	133.98	50.88	0.32	4.78

T35Y - Cooling				
Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
700	138.94	55.29	0.26	2.3
500	164.28	64.87	0.27	1.38
400	174.39	69.02	0.26	1.07
300	181.42	71.63	0.27	1.07
200	187.39	74.04	0.27	1.04
100	192.08	76.14	0.26	1.1
25	195.25	77.45	0.26	0.98

B136Y - Heating				
Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	194.39	77.68	0.25	1.12
25	194.36	77.84	0.25	1.15
100	190.79	76.28	0.25	1.14
200	185.6	74.12	0.25	1.18
300	180.62	72.13	0.25	1.24
400	172.78	68.8	0.26	1.23
500	163.6	64.99	0.26	1.27
600	150.91	59.75	0.26	1.36
700	139.5	55.05	0.27	1.61
800	131.46	51.38	0.28	1.93
850	126.02	49.72	0.27	2.3

C36M2 - Heating				
Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
25	200.91	77.9	0.29	2.38
25	200.79	77.96	0.29	2.44
100	196.67	76.23	0.29	2.44
200	191.75	74.06	0.29	2.45
300	186.54	72.11	0.29	2.42
400	180.61	69.59	0.3	2.74
500	169.43	64.95	0.3	2.77
600	157.06	59.9	0.31	3.03
700	146.32	55.35	0.32	3.46
800	137.79	51.74	0.33	4.64
850	132.89	50.84	0.31	4.31

C36M2 - Cooling				
Temperature [°C]	Elastic Modulus [GPa]	Shear Modulus [GPa]	Poisson's Ratio []	RMS Error [%]
700	144.42	53.43	0.35	3.84
500	169.35	64.64	0.31	4.11
400	179.73	68.9	0.3	3.78
300	187.56	72.19	0.3	3.59
200	193.73	74.76	0.3	3.48
100	198.42	76.7	0.29	3.41
25	202.29	78.34	0.29	3.35