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Rev

IN - 1179
April 1968

A PRIMARY STUDY ON THE COMPRESSIVE
PROPERTIES OF COMPOSITE NUCLEAR FUEL PLATES

MASTER

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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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IN-1179
AEC Research and Development Report
Metals, Ceramics, and Materials
TID-4500
Issued: April 1968

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**U. S. Atomic Energy Commission Research and Development Report
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ABSTRACT

Compression stress-strain curves for Advanced Test Reactor composite, aluminum fuel plates are given for room temperature, 250 (121), 300 (149), 350 (177), 400 (204), 450 (232), and 500°F (260°C). A comparison between 6061-T0 Al and the composite compressive yield strengths indicated significant strengthening affected by the core material. This effect is reflected in Young's modulus above 300°F.

A description of the apparatus used, including the subpress assembly, is given. Also discussed are some problems encountered with this hardware and some probable solutions.

A mechanism is discussed with respect to the strengthening by mechanical interaction of the fuel particles on the matrix.

SUMMARY

The Advanced Test Reactor (ATR) at the National Reactor Testing Station (NRTS) reached criticality during 1967. Because this reactor produces high heat fluxes, a question has been raised with respect to the thermally induced compressive stresses in the aluminum clad ATR fuel plate. A program was initiated to study the compressive yield strength of this fuel plate as a function of temperature. The subpress developed to support the relatively thin test specimen (3.000 x 1.125 x 0.050 or 0.100 inch) functioned properly although some improvements would ease handling problems. Results of the calibration experiments with 2024-T4 Al indicated acceptable results for both the compressive yield strength and compression modulus. The composite nuclear fuel plate (6061-0 Al clad with X8001-Al U₃O₈ core) has a significantly higher compressive yield strength than 6061-0 Al. No significant difference between the modulus of elasticity of 6061 Al and the composite fuel plate was observed up to 300°F (149°C). Above this temperature the composite plate had considerably less elastic deflection than 6061 Al. It is believed that the core acts as an aggregate which raises the flow stress of the ductile matrix by mechanical interaction, thereby accounting for the higher strengths observed. Orthogonal polynomials were used to derive the third degree equation for the room temperature compressive stress-strain curve. The data scatter was attributed to the extensometer supports, specimen lateral support, and plate fabrication.

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I. INTRODUCTION

At the National Reactor Testing Station (NRTS) the Advanced Test Reactor (ATR) reached criticality in July 1967. This reactor is the third in a family of test reactors built by the Atomic Energy Commission in the Test Reactor Area at the NRTS. The ATR core configuration is a four-lobe, serpentine arrangement allowing the reactor to operate with controllable power distribution between lobes. The design summary is given in Table I.

TABLE I

ATR DESIGN SUMMARY

Reactor Configuration	Four-Lobe
Length of Reactor Core (ft)	4
Power Level -- nominal (MW)	250
Fuel Region Volume (liters)	262
Fuel Loading (kg U-235)	39
Estimated Operating Cycle (days)	> 17
Thermal Power Density (MW/liter)	
Maximum	2.8
Average	0.954
Vertical Power Distribution (maximum to average)	1.40
Radial Power Distribution (maximum to average)	2.4
Fuel Annulus Metal-to-Water Ratio	0.75 to 0.80
Primary Cooling Water	
Flow Rate (gpm)	44,000
Velocity in Fuel Channels (ft/sec)	47.5
Inlet Temperature (°F)	130
Inlet Pressure (psig)	350
Reactor Δt (°F)	57
Core Pressure Drop (psi)	100

The ATR serpentine fuel annulus shown in Figure 1 requires a circular sector fuel element consisting of 19 parallel curved fuel plates attached to two side plates to form a 45 degree sector of a right circular cylinder. Forty of these elements depicted in Figure 2 are required for each core loading.

Each plate has an active fueled length of 48 inches with an overall element length of 66-1/4 inches. Plate No 19, the largest plate, is 0.100 in. thick and plate No 1, the smallest plate is 0.080 in. thick to withstand large hydraulic pressure differentials at these two locations. The remaining 17 plates are

Fig. 1 ATR serpentine core configuration made up of 40 individual elements with 19 fuel plates per element.

0.050 in. thick. Because of the voluminous amounts of water required for cooling and the operating temperatures of the ATR, it is mandatory that the coolant channels remain in their specified configuration as shown in Figure 2.

The ATR fuel plates used for the compression test experiments had a core of 51 wt% U_3O_8 with X8001 Al matrix and were clad with 6061-0 Al. A description of the fabrication techniques used in making nuclear fuel plates is available in several reports [1, 2].

Fig. 2 ATR fuel element assembly and details.

1. PURPOSE

Thermal gradients in the ATR fuel plates produce thermal stresses in the plates which act in both the azimuthal and axial directions. The magnitude and distribution of these stresses are directly proportional to the modulus of elasticity of the plate material and to the temperature distribution. Azimuthal thermal stresses cause plate bending, and since the core material contributes only about 19 percent of the plate bending ability, calculations based on aluminum properties have been considered adequate. Axial stresses are of primary interest, however, because they may cause buckling along the plate axis. Although the magnitude of the thermal buckling is self-limiting, buckling could cause plate failure by inducing intolerable hydraulic pressure differentials.

Calculations of axial stresses using aluminum properties indicate that the fuel plate is almost completely in compression, while the side plates are in tension. These calculations also indicate that local temperature peaks will produce longitudinal stresses above the yield point of 6061-0 Al. In order to calculate more exactly the stress distribution, it is necessary to know the compressive behavior of the composite material as a function of temperature; ie, the compressive stress-strain curves at various temperatures and degrees

of irradiation are required. After the stress distributions have been calculated, comparisons with compressive tests of prototype fuel elements will be made to determine the reactor operating conditions at which longitudinal buckling presents a problem [3].

Tensile properties of the core material cannot be used to calculate compressive stresses because the core material is brittle and fractures under tensile stress. This concentrates all of the strain in the aluminum clad material at the point of fracture, giving an erroneous tensile yield point since the theoretical investigation indicated that a portion of the fuel plates will be stressed beyond the proportional limit of the material.

2. EQUIPMENT DESCRIPTION

The equipment described in this report was developed to comply with specification ASTM-E209, "Recommended Practice for Compression Tests". The subpress is capable of operating to 1000°F (538°C) employing resistance-heating externally applied. Compression yield strengths and compression stress-strain curves were plotted via an x-y recorder on the testing machine. The primary problem confronting the operator was specimen misalignment which has been reported [4] by other investigators. To minimize frictional loads, tungsten carbide was used for bearing surfaces and then coated with a suitable lubricant. One additional problem worthy of mention is the loading of the specimen for support. This was accomplished by using standard set screws tightened firmly against the back side of one bearing plate. The screws were backed off and then retightened until a distinct stop was obtained. The procedure was repeated until there was no detectable motion of the bearing block.

To determine Young's modulus, a load-unloading technique was used taking advantage of the nearly perfect isotropic behavior of aluminum. Physically, the load was applied to slightly above the yield point, then unloaded to zero, and finally reloaded. The reloading line paralleled the elastic portion of the curve, resulting in a longer and generally easier read line from which to calculate the modulus. It should be noted that the modulus measurements using the specimen described are not as precise as measurements taken to comply with ASTM-E111-61; however, the modulus values given do give an indication of the general behavior of the compression modulus as a function of temperature.

II. DESCRIPTION OF EQUIPMENT

1. TESTING MACHINE

The testing machine depicted in Figure 3 is an Instron Universal Testing Machine, model TT-D, equipped with a compression overload carriage housing the Instron GR combination tension-compression load cell. An additional load weighing accessory was employed such that stress-strain curves were plotted directly. A dial-controlled (area compensator) circuit enabled the operator to vary the calibration of the weighing system to compensate for the cross-sectional area of each sample, thereby enabling stress to be recorded directly.

Fig. 3 Instron universal testing machine setup with compression testing subpress for compression testing nuclear fuel plates. (Furnace not shown.)

The other coordinate was extensometer controlled via an x-y chart drive system. The extensometer was attached to the specimen with extension rods allowing the strain measurement to be recorded directly. The extensometer used for all the tests was a G-15-13 Instron strain gage extensometer calibrated according to ASTM-E83-64T. Having a two-inch gage length, this extensometer was classed as B-1, indicating a maximum error of 0.0001 indicated strain. The

B-1 class of extensometer is acceptable for determining modulus and yield strength of metallic materials according to the specification noted. Verification resulted in a calibration factor in deflection of 0.502.

2. SUBPRESS

A subpress assembly provided specimen support as shown in Figure 4. The bearing support assembly, bearing block guide, push rod, and extensometer support ring are made with Inconel 750X. Grooved tungsten carbide blocks were used to prevent buckling during loading. Longitudinal grooves were cut in each bearing plate such that the grooves were offset across the width of the specimen.

INC-C-11558

Fig. 4 Details of the compression testing subpress used for testing thin plates.

Although the maximum test temperature was 500°F (260°C) during this series of tests, it is expected that the subpress is suitable for operating to 1000°F (538°C).

External resistance heating supplemented by radiant heating was accomplished by a thermocouple controlled, split Marshall furnace.

III. TEST SPECIMEN

The test specimen, depicted in Figure 5, consisted of 6061-0 Al cladding with a depleted U_3O_8 -X8001 Al intermediate dispersion layer 0.020 inch thick. The cladding material was 0.040 inch thick in the first series of tests and 0.015 inch thick in the second series. All specimens were 3.000 x 1.125 inches including the 2024-T4 Al calibration samples. The test specimens were cut from full-size ATR fuel plates after roll leveling (to flatten) and annealing. The latter treatment was to ensure the annealed condition was preserved as set forth in the ATR specifications. The specimens were sheared to the approximate dimensions and then machined to final size. Care was taken to remove at least enough material during the machining operation to equal the thickness of the plates. The machining jig used to trim the ends is depicted in Figure 6. The surface remained in the as-rolled condition, eg, 63 microinches or better.

Fig. 5 Schematic of nuclear fuel plate compression testing and calibration specimen showing dimensions.

Fig. 6 End machining jig used in conjunction with a Tensilkut machine to finish the compression test specimen end dimensions.

IV. RESULTS

1. 2024-T4 Al CALIBRATION

Calibration of the subpress using 2024-T4 aluminum gave excellent results at room temperature. As shown in Table II yield strength measurements were well within the five percent deviation specified in ASTM-E209. The average yield strength (0.2 percent offset) was 46,000 psi in compression for three tests, comparing favorably with the published^[5] tensile strength value of 47,000 psi and certification of conformance tensile value of 42,000 psi.

TABLE II

SUMMARY OF CALIBRATION DATA FOR 2024-T4 Al 0.050-INCH-THICK PLATE TESTED IN COMPRESSION AT ROOM TEMPERATURE AND 500°F (260°C)

Sample	Test Temperature (°F)	Soaking Time at Temperature (min)	Yield Strength 0.2% Offset (psi)	Modulus of Elasticity (psi)
A-1	75 (24°C)	---	45,300	10.5×10^6
A-2	75	---	46,500	10.3×10^6
A-3	75	---	46,300	10.5×10^6
E-1	500 (260°C)	30	41,000	8.1×10^6
E-2	500	30	38,000	9.1×10^6
Published yield strength at room temperature in tension				
Alcoa Aluminum Handbook ^[5]				47,000 psi
Certification of Conformance				42,000 psi

Because the soaking time of 30 minutes was insufficient to cause significant precipitation, tests conducted at 500°F indicated a strength level higher than the "0" or full annealed condition. However, considering the aging behavior of 2024-T4 Al, the test results were well within realizable limits, averaging 39,500 psi as shown in Table II. The drop observed (from 46,000 psi to 39,500 psi) in yield strength from the T4 heat treatment condition is consistent for this alloy^[6].

Modulus-of-elasticity measurements were satisfactory at the two testing temperatures for the 2024-T4 Al calibration samples. The results shown in Table II give an average modulus at room temperature of 10.4×10^6 and 8.6×10^6 psi at 500°F. The reported values for these measurements are 10.7×10^6 psi at room temperature and slightly more than 80 percent of this value at 500°F^[7]. Because of the nearly perfect elastic isotropy of aluminum, the elastic modulus is nearly the same in both the tensile and compressive testing modes.

Also, the moduli of elasticity of aluminum alloys are dependent upon composition and independent of temper, product, and direction of cold work. Therefore, it is readily seen that the increased elastic deflection at the elevated temperature is somewhat independent of the high yield strength as noted above.

2. COMPOSITE PLATE

To maintain clarity, only the average result values are summarized in Figure 7 for the composite nuclear fuel plate. The reader is referred to the individual compressive stress-strain curves shown in Section V (Figures 8 through 14) where each test is plotted separately.

Fig. 7 Summary of compression testing data comparing test results with published values for 6061-0 Al. Yield strength and modulus versus temperature.

It is immediately noted that the fuel plate composite maintains a significantly higher yield strength than the cladding material alloy. This is especially evident at temperatures above 300°F (149°C). The published^[26] yield strength of 6061-0 at room temperature is about 8000 psi, whereas the fuel plate composite compressive yield strength exceeds 11,000 psi (0.2 percent offset) at the same temperature. This difference holds up to about 300°F (149°C) where the tensile yield strength of 6061-0 Al starts to drop rapidly to about 4,500 psi at 500°F (260°C). The compressive yield strength for the composite is about 10,300 psi at 500°F (260°C). Apparently the core significantly stiffens the composite. This is again seen in the modulus of elasticity measurements where the value for the aluminum alloy alone drops from 10×10^6 to about 8.0×10^6 psi from room temperature to 500°F (260°C), respectively. The composite, on the other hand, maintains a slightly higher value of about 10.4×10^6 and does not start to drop significantly until 400°F (204°C). Even at 500°F (260°C) the modulus had only dropped to 9.4×10^6 psi.

V. ANALYSIS

1. EQUATION FOR ROOM TEMPERATURE STRESS-STRAIN CURVE

To assist potential users of the stress-strain curves (Figures 8 through 14), an equation for the room temperature curve was derived using orthogonal polynomials. This is a standard correlation technique used with data recorded at regular intervals [8].

Fig. 8 Compression stress-strain curve for the composite nuclear fuel plate at room temperature.

The data were first coded to ease handling, then the F statistic was applied to determine the significant polynomial degree. It was found that the fourth term was insignificant at a 0.01 confidence level resulting in a cubic curve taking the form

$$\epsilon = \beta_1 \sigma^3 + \beta_2 \sigma^2 + \beta_3 \sigma + \beta_4 \quad (1)$$

Fig. 9 Compression stress-strain curves for composite nuclear fuel plates at 250°F (121°C).

where ϵ is the measured strain and σ is the stress. The actual equation for the room temperature engineering stress-strain curve is

$$\epsilon = 4.1 \times 10^{-14} \sigma^3 - 8.1 \times 10^{-10} \sigma^2 + 5.5 \times 10^{-6} \sigma - 1.1 \times 10^{-2} \quad (2)$$

This equation is valid between 5000 and 13,000 psi and should not be used outside this range. It is assumed, because of the physical nature of the test, that essentially a straight line relationship between stress and strain exists between 0 and 5000 psi. This would be included in the elastic portion of the curve and would obey Hooke's Law.

$$E = \frac{\sigma}{\epsilon}$$

As a check for Equation (2), values of ϵ for a given σ were plotted in Figure 8 along with the experimental values.

Fig. 10 Compression stress-strain curves for composite nuclear fuel plates at 300°F (149°C).

Fig. 11 Compression stress-strain curves for composite nuclear fuel plates at 350°F (177°C).

Fig. 12 Compression stress-strain curves for composite nuclear fuel plates at 400°F (204°C).

Fig. 13 Compression stress-strain curves for composite nuclear fuel plates at 450°F (232°C).

Fig. 14 Compression stress-strain curves for composite nuclear fuel plates at 500°F (260°C).

2. STRENGTHENING MECHANISMS

It is well known that large stresses are difficult to achieve when a metal deforms easily by slip. From these tests, it seems reasonable to conclude that the fuel concentration in the core region is sufficient to inhibit slip and cause a significant increase in yield strength. This is further supported by considering the stress state in the core area. The maximum shear stresses are operating in a plane parallel to the supported surfaces and 45° to the loading direction. It is assumed that the shear strength of the fuel particle is much higher than the matrix or cladding; consequently, all deformation occurs in these areas. As the stress begins to build, dislocations start to move in the material and will continue to progress until some obstruction such as a defect or grain boundary, is encountered. The dislocations will then pile up around the obstruction with increasing stress until the material is strained beyond its proportional limit where plastic

flow begins. Since the core region is impregnated with relatively hard particles, providing stops, more dislocations must pile up before measureable plastic flow will begin.

The composite nuclear fuel plate, strictly speaking, should be called a laminated aggregate since particles of a hard phase (fuel) are distributed in a softer matrix (aluminum) with aluminum cover plates on each side. However, the term "composite" is generally used where the volume fraction of the hard phase is large (20 to 80 percent). Tetelman and McEvily [9] report that when a crack initiates at a surface flaw in the brittle phase that is surrounded by an inherently notch-tough matrix (such as aluminum), the crack will be blunted and stopped when it reaches the softer matrix. This may result in plastic deformation of the matrix causing splitting, which in turn deflects the crack out of the plane in which it had been propagating.

Gurland [10] studied the relationship between the mean free path of the brittle phase and fracture strength of tungsten carbide-cobalt cemented alloys. Maximum strength is achieved at a transition between two fracture modes when the structure and load satisfy conditions for spontaneous crack propagation. Above the critical value of the mean free path the fracture process is discontinuous, and below the critical value the Griffith fracture criterion applies. In a study with similar material, Nishimatsu and Gurland [11] found that the greater the percentage of tungsten carbides in the alloy, the lower the load at which localized deformation occurred in the elastic portion of the load deformation curve. In the cobalt-rich alloys (low percentage of tungsten carbide) the alloy failed without requisite fracture of the tungsten carbide particles. The load is carried primarily by the matrix, and the function of the brittle phase is to raise the flow stress of the ductile matrix by mechanical interaction. This is the situation with the nuclear fuel plate composite since the volume of the fuel is between 20 and 35 percent. The flow strength of the matrix is much lower than that of the fuel so that plastic deformation begins in the matrix while the hard phase remains elastic [11]. A biaxial stress configuration is established which requires a higher nominal stress to continue plastic deformation.

3. DATA SCATTER

Analyzing the data presented in the Figures 8 through 14, one notes significant scatter in the data, especially at the higher stress levels. Contributions of this data scatter can be traced to two sources. Because this is a new area of endeavor, considerable study and training were necessary. The subpress assembly was designed after several assemblies described in the literature [12] with certain modifications to make the subpress adaptable to the equipment on hand. Major components requiring improvement are the extension ring supports noted in Figure 4. These rings were supported at two points on opposite edges of the specimen and alignment support through the extensometer arrangement. Although extreme care was exercised in aligning this fixture, tilting was difficult to eliminate. To minimize this effect, it is suggested that the extension ring supports be changed to a split-bearing arrangement so that the ring supports will ride on the bearing support, also shown in Figure 4.

The second contribution to the data scatter can be traced to manufacturing techniques used to make the nuclear fuel plate from which the specimens were

taken. The fuel plates are fabricated using powder metallurgy techniques and roll-bonding methods. The fuel and matrix powders are weighed, blended, compacted, and inserted into a restraining picture frame. Then cover plates are fastened to each side of the picture frame and hot rolled. It is during the rolling stage that the fuel concentration shifts slightly, causing heavier loading in one area than another. This is an inherent rolling defect reported by other investigators [13] on rolling metal powders. Conceivably then, samples previously described taken from a plate 48 inches long and 2 inches wide could have slightly different mechanical properties.

An additional factor causing this scatter is associated with the lateral support. The apparatus would not allow the test specimen under axial compressive strain to increase freely, affecting Poisson's ratio. This would cause the test specimen to be stiffened against the axial compressive load, raising somewhat the compressive yield strength and modulus. Some investigators [14] have compensated this influence by using springs to load the bearing block supports.

VI. CONCLUSION

The primary purpose of this investigation was to determine the compressive stress-strain properties of the ATR composite nuclear fuel plates. This has been accomplished with the significant conclusions that:

- (1) The compressive yield strength of fuel plates clad with 6061-0 Al and a 51 wt% U_3O_8 -X8001 Al powder metallurgy core is approximately 37 percent higher than 6061-0 Al up to 300°F (149°C).
- (2) The difference between the yield strengths of the fuel plate and 6061-Al increases from about 3000 psi at 300°F (148°C) to 5700 psi at 500°F (260°C).
- (3) The compressive modulus of the fuel plate composite is not significantly different than that of 6061-0 Al up to about 300°F (149°C).
- (4) The increased compressive strengthening is reflected in compressive modulus measurements above 300°F (149°C). The curve remains reasonably flat at about 10.5×10^6 psi from room temperature to 300°F (149°C) where the values start to drop, ultimately to 9.4×10^6 psi at 500°F (260°C), as opposed to 8.0×10^6 psi at 500°F (260°C) for 6061-Al.
- (5) The proposed strengthening mechanism is believed to be caused by a plastic constraint through a mechanical interaction of the brittle phase (fuel) with the load-bearing matrix. Further investigation should pursue the effects of fuel concentration on the mechanical properties of the composite nuclear fuel plates. However, before this the apparatus described herein should be modified to accommodate thermal expansion effects and extension measurements.

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