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OL-1316

MASTER

Y-1985

**A DIRECTIONALLY SOLIDIFIED URANIUM-
SILICON HYPOEUTECTIC COMPOSITE**

R. C. Anderson

May 1975

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OAK RIDGE, TENNESSEE**

*prepared for the U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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Date of Issue: May 6, 1975
Distribution Category: UC-25

Report Number: Y-1985

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R. C. Anderson

Metallurgical Development Department
Y-12 Development Division

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Oak Ridge Y-12 Plant

P. O. Box Y, Oak Ridge, Tennessee 37830

Prepared for the US Energy Research
and Development Administration

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ABSTRACT

When uranium-0.763 wt % silicon (hypoeutectic) is directionally solidified, an in situ composite is formed. This composite must be heat treated to decompose the U_3Si_2 (formed during solidification) to U_3Si in order to achieve the increased strength, ductility, and modulus of elasticity that the composite is capable of exhibiting. The mechanical properties of this hypoeutectic composite are lower than for high-strength uranium alloys.

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SUMMARY

Uranium-0.763 silicon (U-0.763 Si) alloy will form a rod and lamellar eutectic structure when directionally solidified to form an in situ composite.

A brittle, intermetallic phase (U_3Si_2) forms during solidification. This phase must be decomposed to U_3Si by heat treatment to achieve the increased strength, ductility, and modulus of elasticity that the composite is capable of attaining. Conversely, heat treatment coalesces the U_3Si intermetallic phase and decreases the yield strength of the composite.

INTRODUCTION

Fiber-reinforced composites have received considerable attention because they may be designed to obtain an optimum combination of strength and ductility for structural applications. However, many of these composites are "artificial" or "handmade" and are difficult to manufacture. Directional solidification of eutectics to produce parallel arrays of thin, filamentary (high-strength) crystals of one phase, embedded in a matrix of another (ductile) phase is a unique approach to the production of fiber-reinforced composites.

The mechanical properties of a directionally solidified uranium-silicon hypoeutectic alloy were determined and compared with the properties of a conventionally cast alloy of the same composition at the Oak Ridge Y-12 Plant.^(a)

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

FORMING A URANIUM-SILICON HYPOEUTECTIC ALLOY

EXPERIMENTAL WORK

Melting and Solidification

A uranium-silicon master alloy containing 3.5 wt % silicon was made by comelting 99.999% pure silicon with derby uranium in a zirconite-coated, graphite crucible in a vacuum-induction furnace at 1550° C, and dud cast.

The master alloy from the dud casting and derby uranium was then comelted in the same manner and cast into a five-rod cluster mold. Each rod was 20.5 mm in diameter and 139.7 mm long. One rod cluster was used as the control or conventionally cast hypoeutectic alloy containing 0.763 wt % silicon; a second rod cluster was retained in the mold, placed in the induction coil of the vacuum-induction furnace, and heated to approximately 1180° C to melt the alloy before lowering the mold out of the coil at a constant rate of 38 mm per hour to initiate and continue directional solidification of the hypoeutectic, composite rods.

Alloy Analysis

Chemical and spectrographic analyses were conducted on the alloy and are presented in Table 1.

Morphology

Conventionally cast U-0.763 Si alloy has a typical hypoeutectic structure consisting of two intermetallic compounds (U_3Si and U_3Si_2) in a matrix of alpha uranium, as shown in Figure 1.

Unidirectional solidification of the hypoeutectic alloy produced some alignment of the intermetallic phase, forming both a rod and lamellar structure. Typical transverse and longitudinal microstructures are presented in Figures 2 and 3, respectively.

Examination of the fractured surfaces of tensile specimens (Figure 4) revealed that several had a silvery-colored structure that had grown transverse to the anticipated direction of solidification. Figure 5 presents a scanning electron micrograph of this structure. An X-ray diffraction analysis of the silvery structure (Figures 4 and 5) established the presence of alpha uranium (matrix) and U_3Si_2 .

When the directionally solidified hypoeutectic alloy was heat treated at 650 or 760° C for 50 hours in a vacuum of 6.7 mPa, or better, a microstructure, seen in Figure 6, formed. X-ray diffraction analysis after this heat treatment revealed that the alloy was composed of only alpha uranium and U_3Si .

A scanning electron micrograph of the rod and lamellar structure of directionally solidified hypoeutectic alloy can be seen in Figure 7. Figure 8 shows the structure after heat treating at 760° C for 50 hours.

H426

Figure 1. MICROSTRUCTURE OF CONVENTIONALLY CAST URANIUM-0.763 SILICON ALLOY. (Bright Field Illumination; 100X)

H471

Figure 2. MICROSTRUCTURE OF THE TRANSVERSE SECTION OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY. (Bright Field Illumination; 100X)

H448
Figure 3. MICROSTRUCTURE OF THE LONGITUDINAL SECTION OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY. (Bright Field Illumination; 100X)

H560-1
Figure 4. PHOTOMACROGRAPH OF THE FRACTURED SURFACE OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY. (10X)

157174

Figure 5. SCANNING ELECTRON MICROGRAPH OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY. (White, Lamellar Structure is U_3Si_2 ; 3000X)

K87-2

Figure 6. MICROSTRUCTURE OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY AFTER A 650° C, 50-HOUR HEAT TREATMENT. (Bright Field Illumination; 100X)

157173
Figure 7. SCANNING ELECTRON MICROGRAPH OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY. (Etched to Show the Intermetallic Compound in Relief; 3000X)

157175
Figure 8. SCANNING ELECTRON MICROGRAPH OF THE DIRECTIONALLY SOLIDIFIED URANIUM-0.763 SILICON ALLOY AFTER A 760° C, 50-HOUR HEAT TREATMENT. (3000X)

Microprobe Examination

An ion microprobe analysis was run on the directionally solidified alloy to determine the amount of silicon present in the alpha uranium matrix. The examination was carried out using a positively charged, 12- μ m-diameter, nitrogen ion beam. Mass spectra were obtained from the matrix, and the intensities of the major peaks were obtained by pulse counting. The silicon in the matrix appeared to be present in small inclusions or particles which may be an intermetallic compound. The silicon content of the intermetallic compound present was only 1.5 times the silicon content of the matrix. This result indicates that the silicon content of the matrix was much greater than the 170 ppm quoted in the literature^(b) or that the beam of the ion microprobe was not exclusively on the alpha uranium phase.

Table 1
CHEMICAL AND SPECTROGRAPHIC
ANALYSES OF A URANIUM-SILICON
HYPOEUTECTIC ALLOY

Element	Amount Present ⁽¹⁾	Element	Amount Present ⁽¹⁾
Al	40	Mg	< 2
As	< 10	Mn	5
Au	< 1	Mo	< 10
B	< 0.1	Na	< 1
Ba	< 2	Nb	> 100
Be	< 0.1	Ni	8
Bi	< 1	P	< 100
C	400	Pb	< 5
Ca	< 10	Pd	< 1
Cd	< 0.1	Sb	< 2
Co	< 1	Si	0.763 wt %
Cr	4	Sn	< 10
Cu	8	Sr	< 20
Fe	100	Ti	< 4
Ga	< 1	V	< 1
Ge	< 1	W	< 100
Li	< 0.2	Zn	< 10

(1) All values in ppm, except as noted.

(b) Straatmann, J. A. and Neumann, N. F.; *Equilibrium Structures for the High Uranium-Silicon Alloy System*, MCW - 1486; Mallinckrodt Chemical Works, Weldon Spring Plant, Missouri; October 23, 1964.

Mechanical-Property Data

Tensile specimens with 6.35-mm reduced sections were ground from both the control and directionally solidified rods, and tested. The mechanical properties of these two groups of specimens are listed in Table 2. Ends from the directionally solidified tensile specimens were heat treated at 650 and 760° C for 50 hours, and tensile specimens with 3.17-mm reduced sections were ground and tested. The resulting mechanical properties are presented in Table 3.

RESULTS

Directional solidification of the U-0.763 Si alloy did not increase the tensile strength of the composite, but did increase the yield strength and modulus of elasticity when compared to the same properties for conventionally (control) cast alloy.

Both castings had extremely low ductility, due, probably, to the presence of U_3Si_2 , which is a very brittle intermetallic compound, and to its formation in the transverse direction during directional solidification.

Table 3
MECHANICAL PROPERTIES OF HEAT-TREATED HYPOEUTECTIC ALLOY

Tensile Strength (MPa)	Yield Strength ⁽¹⁾ (MPa)	Elongation ⁽²⁾ (%)	Modulus of Elasticity (GPa)
<u>650° C - 50 Hrs</u>			
847.4	402.1	8	200.6
819.0	386.1	8	220.6
844.5	373.4	8	169.6
<u>760° C - 50 Hrs</u>			
748.7	356.0	8	165.4
822.8	347.5	9	128.9
<u>717.2</u>	<u>305.8</u>	<u>5</u>	<u>171.0</u>
Average	799.9	7.7	176.0

(1) At 0.2% offset.

(2) In 12.7 mm.

Table 2
MECHANICAL PROPERTIES OF THE URANIUM-SILICON HYPOEUTECTIC ALLOY

Tensile Strength (MPa)	Yield Strength ⁽¹⁾ (MPa)	Elongation ⁽²⁾ (%)	Reduction in Area (%)	Modulus of Elasticity (GPa)
<u>Control</u>				
639.1	506.0	< 1	0	124.1
645.9	484.6	< 1	0	131.6
561.2	526.0	< 1	0	139.2
632.9	490.8	< 1	0	130.3
546.0	494.2	< 1	0	133.7
605.0	500.3	< 1	0	131.8
<u>Directionally Solidified Alloy</u>				
663.2	576.3	< 1	0	140.6
727.3	623.2	< 1	0	148.2
463.9	-	< 1	0	139.2
567.3	550.8	< 1	0	135.1
605.4	583.4	< 1	0	140.7

(1) At 0.2% offset.

(2) In 25.4 mm.

When U_3Si_2 was decomposed to U_3Si by heat treating, coalescence of the intermetallic phase took place, as noted in Figures 6 and 8. The tensile strength, ductility, and modulus of elasticity increased appreciably, but the yield strength decreased.

The lower heat-treating temperature of 650° C resulted in somewhat higher mechanical properties than for the 760° C treatment.

CONCLUSIONS AND RECOMMENDATIONS

This study points out the need for future work which should include the following:

1. Increase the silicon content to 1.2 wt % (eutectic composition).
2. Decrease the rate at which the mold is lowered from the induction coil to reduce the breakdown into a cellular front that causes the rods and plates to fan out in the structure.
3. Determine the optimum heat treatment for maximum U_3Si_2 decomposition and minimum coalescence of U_3Si in the alloy.

Mechanical properties of the heat-treated, hypoeutectic composite are lower than for high-strength uranium alloys; consequently, it is not a competitive system at the present time.

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