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THE FABRICATION OF STAINLESS STEEL - URANIUM DIOXIDE FUEL ELEMENTS

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J. R. Keeler
D. L. Keller
L. J. Cuddy

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THE FABRICATION OF STAINLESS STEEL - URANIUM DIOXIDE FUEL ELEMENTS

J. R. Keeler, D. L. Keller, and L. J. Cuddy

Stainless steel-clad fuel sheet 0.020 in. thick with a 0.008-in. core of stainless steel plus UO_2 was produced by roll cladding a powder-metal compact. The effects of processing variables, core-matrix composition, quantity of oxide, and oxide particle size on the properties of the sheet were investigated. The strength and ductility of the core decreased sharply as the quantity of oxide in the core increased from 20 to 40 w/o. Over the range of matrix compositions investigated, the particle size of the oxide had little effect on the core strength. In cores containing 25 w/o of oxide, an 18 w/o chromium - 82 w/o iron matrix prepared from the elemental metal powders had the highest strength and ductility, but this matrix was susceptible to cracking during thermal cycling. An elemental 18 w/o chromium - 9 w/o nickel - 73 w/o iron matrix was the most satisfactory from the standpoint of fabrication and over-all characteristics of the resulting sheet.

INTRODUCTION

Pratt & Whitney Aircraft is making a study of the feasibility of a supercritical-water reactor for aircraft propulsion. As a part of this study, Battelle Memorial Institute is developing fuel elements for the reactor core. *Ed*

The initial design studies for this reactor were made by the Nuclear Development Associates. In these studies, a 0.020-in.-thick sheet-type fuel element having 0.006 in. of stainless steel cladding on an 0.008-in.-thick core of stainless steel plus UO_2 appeared to be the most practical for meeting the conditions of heat transfer and corrosion expected.

Considerable development work on this type of fuel element had been done at ORNL and by GE-ANP. The program at Battelle was directed toward improving the methods of preparing the clad sheet and toward studying the fabricating characteristics of the resultant sheet.

Powder-metallurgy techniques were used to prepare the core, which was subsequently roll clad with Type 347 stainless steel. The effects of rolling conditions as well as the composition of the core were investigated.

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PREPARATION OF CORE COMPACTS

Uranium dioxide was selected as the fuel material because of its availability and high uranium concentration as well as the chemical inertness and stability it possesses at elevated temperatures. In order to fabricate a clad sheet with a core containing uniform dispersions of UO_2 , it was necessary to employ powder-metallurgy techniques for the preparation of core compacts.

Several different metal powders were investigated as possible matrix materials in an effort to obtain a core with suitable corrosion resistance, strength, and ductility. The formation of a strong, ductile bond between the core and Type 347 stainless steel cladding would also depend largely on the selection of the matrix material.

Materials

The materials used in the preparation of the fuel-element cores were initially in powder form. The principal powders considered for the matrix were electrolytic iron; a mixture of electrolytic iron and electrolytic chromium; various mixtures of electrolytic iron, carbonyl nickel, and electrolytic chromium; and prealloyed Types 347 and 302 stainless steels. Prealloyed Types 316 and 302B stainless steel powders were investigated less extensively.

The particle-size distribution of the minus 325-mesh powders of iron, nickel, chromium, and Type 347 stainless steel is shown in Figure 1. The Types 302, 302B, and 316 stainless steel powders were minus 200 mesh. All of these metal powders were supplied by the Charles Hardy Company. The spectrographic and chemical analyses of these powders are shown in Table 1.

"Project"-grade natural UO_2 , in the form of particle dispersions in the metallic core matrix, was used as fuel. The UO_2 was analyzed and found to contain only 86.2 w/o uranium compared with the theoretical value of 88.03 w/o. The dioxide was the only oxide of uranium detected by X-ray diffraction techniques.

Uranium dioxide particles in size ranges of 0 to 3 microns, 0 to 53 microns, 5 to 44 microns, and 44 to 53 microns were used to study their effect on the properties of the fabricated sheet. The coarse separations were made with standard screens. The 5- to 44-micron size range was the product of the first six cones on a Haultain Infralyzer, and the minus 3-micron fraction was the bag product of this elutriator. The particular

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FIGURE 1. PARTICLE-SIZE ANALYSIS OF CHROMIUM, IRON, NICKEL, AND TYPE 347 POWDERS BY THE CASAGRANDE HYDROMETER METHOD

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TABLE 1. ANALYSIS

Type of Powder	Fe	Ni	Cr	Si	Mn
Electrolytic Iron	Bal.	0.005 to 0.05		0.003 to 0.03	0.002 to 0.02
Carbonyl Nickel	0.002 to 0.02	Bal.		0.001 to 0.01	
Electrolytic Chromium	0.06	0.005		0.007	
Type 347(a)	Bal.	10.74	17.98	2.39	1.31
Type 302(a)	Bal.	8.86	18.58	1.05	0.59
Type 316(a)	Bal.	11.09	17.72	2.44	0.89
Type 302B(a)	Bal.	8.14	17.43	2.53	0.81

(a) Stainless steel; supplier's analysis.

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OF METAL POWDERS

Analysis, w/o						
C	S	P	Mo	Al	Cu	Others
0.06	0.019	<0.01	0.0005 to 0.005	0.005 to 0.05	0.0003 to 0.003	0.0005 to 0.005 Mg 0.001 to 0.01 Ca
0.12	0.003	<0.01				0.0009 Mg
	0.004	<0.01	0.001	0.005	0.005	0.005 Ca
0.06	0.008	0.014				0.73 Cb
0.09	0.007	0.029				
0.08	0.006	0.025	2.47			
0.10	0.008	0.023				

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size ranges chosen represented a fine, an intermediate, and a coarse range. The 44- to 53- micron particle diameters were approximately one-fourth the thickness of the core.

Powder-Metallurgy Techniques

The UO_2 and metallic powders, which together made up the core, were blended by tumbling on laboratory rolls 1/2 to 1 hr. Very fine UO_2 powder was difficult to mix because of its tendency toward particle agglomeration.

The addition of a few steel washers during tumbling aided in breaking apart the agglomerates and resulted in a well-blended mixture.

A weighed amount of the blended powders was loaded into a single-action segment-type die where it was cold pressed at 100,000 psi. A green compact measuring approximately 1 by 1 by 1/8 in. was ejected by applying a light load to the die punch. A pressure of 100,000 psi yielded green compacts having satisfactory green strength and performance during sintering, with few ejection failures. Lower pressures resulted in more fragile green compacts, having slightly lower densities, particularly in the case of compacts with prealloyed-stainless steel matrices. Compacts produced at higher pressures showed no appreciable increase in sintered densities. The green densities of the cold-pressed compacts averaged about 75 per cent of theoretical density.

The die walls and punches were lubricated with a thin film of stearic acid. No internal lubricant was added to the powders themselves.

Sintering was done in a muffle-type furnace under a dry hydrogen atmosphere (about minus 55 F dew point) for 4 hr at 2200 F. Densification during sintering varied with the type matrix as well as with the concentration and particle size of the UO_2 . As expected, densification was reduced with increasing amounts of UO_2 and with decreasing UO_2 particle size. Compacts with either an iron or a prealloyed-stainless steel matrix showed a definite increase in density during sintering. Sintering compacts with matrices made from mixtures of iron, nickel, and chromium powders showed either no change or a decrease in density, depending upon the concentration and particle size of the UO_2 used.

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FABRICATION OF CLAD SHEET

Jacketing

After sintering, the powder-metal compact was jacketed by the picture-frame technique and rolled to sheet. A segmented type of picture frame was used. Four pieces of Type 302 stainless steel having the same thickness as the core compact were spot welded to one cover plate of Type 347 stainless steel to form a 1-in.-wide frame around the core. This frame was pickled to remove the welding scale and then dried. The powder-metal compact was lightly abraded, placed in the frame; and the second Type 347 cover clamped in place. The four edges of the pack were welded closed with a shielded tungsten arc in a vacuum-purged, argon-filled welding tank.

Roll Cladding

The welded packs were hot rolled to sheet approximately 0.026 in. thick and finished by cold rolling to 0.020 in. The samples were heated for rolling in an electric muffle-type furnace in an argon atmosphere. After each pass, the samples were reheated and the direction of rolling reversed to equalize the effect of the rapid cooling of the thin sheet during the passage through the rolls.

Effect of Process Variables

Several samples were rolled to investigate the effect of rolling temperature, rate of reduction, and direction of rolling on the oxide distribution in the core. Rolling temperatures of 1850, 2200, and 2300 F were investigated. The tendency to form stringers of oxide in the core decreased when the rolling temperature was increased from 1850 to 2200 F. A further increase to 2300 F caused no additional improvement in structure, and scaling was much more rapid at the higher temperature. Raising the rolling temperature from 1850 to 2200 F had practically no effect upon the tensile strength of the samples.

In samples rolled at 2200 F, the rate of reduction had only a slight effect on the oxide distribution in the core. With light reduction, approximately 10 per cent per pass, there was a greater tendency for oxide stringers to form than with reductions of 25 to 50 per cent per pass. Cross rolling also tended to reduce the tendency toward the formation of

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stringers. These effects were not marked and other factors such as matrix composition had a much greater effect on oxide distribution.

The rolling schedule, shown in Table 2, was adopted because experience has shown that heavy reductions tend to improve the quality of the bond. In this schedule, an initial reduction of 50 per cent was made in the first pass in a longitudinal direction. The compact was then cross rolled to twice its original width in two passes.

After cross rolling, the pack was cooled and sandblasted, and excess cladding was sheared from the edges. Subsequent passes were in a longitudinal direction. The sample was turned end for end and flipped over between each pass to minimize the effect of rapid cooling of the thin sheet during passage through the rolls. Without such manipulation, the core was thicker at the trailing end than at the leading end of the sheet, and the cladding thickness was greater on one side of the sheet than on the other side.

After hot rolling, the sheet was pickled to remove scale and cold rolled to 0.020 in. The cold-rolled sheet was annealed 1/2-hr at 1850 F. This anneal resulted in a recrystallized fine-grained structure in the cladding and core. Annealing at higher temperatures and for longer times resulted in grain growth in the cladding material, but the grain size of the core generally remained small because of the UO_2 inclusions.

EXAMINATION OF ROLL-CLAD SHEET

In order to determine the effect of core-matrix composition, oxide content, and oxide particle size on the properties of the clad sheet, a series of tests was made on each sample.

Bend Tests

In the initial design studies by NDA, a corrugated-flat-plate configuration for the sheet-type fuel elements was proposed. The corrugations in the 0.020-in.-thick fuel sheet were to be 0.109 in. high and have an inside bend radius of 0.010 in. A bend test was therefore made on the fabricated sheets to determine the minimum-radius bend that could be made parallel to the rolling direction without cracking either core or cladding. Six samples of each sheet, 1/2 in. wide, were cut and bent in a 75-deg V-die by means of punches having radii of 1/8, 3/32, 1/16, 3/64, 1/32, and 1/64 in. The bent samples were mounted in bakelite and examined

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TABLE 2. HOT-ROLLING SCHEDULE FOR PACKS

Pass	Roll Setting, in.	Typical Actual Thickness, in.	Reduction, per cent	Direction of Pass	Remarks
Initial		0.310	--		
1(a)	0.133	0.156	50	Longitudinal	
2	0.092	0.113	28	Cross roll	Rolled 90 deg from Pass 1 and flipped over
3(b)	0.053	0.079	30	Cross roll	Same side and direction as Pass 2
4	0.025	0.059	25	Longitudinal	Same direction as Pass 1
5	0.015	0.044	25	"	Turned 180 deg and flipped over
6	0.005	0.033	25	"	Ditto
7	0.000	0.027	18	"	"
8	0.000	0.026	4	"	"

(a) Samples reheated after each pass.

(b) After Pass 3, samples were sandblasted and sheared to remove excess edge cladding.

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metallographically to determine the radius of the bend at which cracking occurred.

Two other simple bend tests were made. A 1/4-in.-wide strip of the clad sheet was clamped in a vise which had a 7/64-in. radius on the jaws. The strip was then bent 90 deg in one direction and back through 180 deg by means of a roller. The 180 deg reversals were repeated until the strip broke. All of the samples tested broke after 9 to 14 reversals, but there was no indication of separation or failure in the bond between core and cladding.

In the second test, a 1/4-in.-wide by 3-in.-long strip of the clad sheet was clamped at the ends and twisted lengthwise until the strip broke. The number of twists and the appearance of the break were noted.

Neither of these tests was sensitive enough to indicate significant differences between the various sheets. However, both tests, and a chisel test, indicated that the strength of the bond between core and cladding was greater than that of the core itself. In all cases, cracking occurred in the core rather than at the interface.

Transverse Tensile Strength

Similar indications were observed in the tensile tests in a direction normal to the surface of the sheet. This transverse tensile strength was measured by brazing extension bars on opposite sides of a small specimen of the sandwich sheet. Tensile bars with the sheet at the center of the reduced section were turned from the brazed assemblies and these bars were pulled at room temperature. The strength of the clad-to-core bond or the core, whichever was weakest, was thus obtained. Figure 2 shows a cross section through the broken end of a tensile bar. It is evident that failure occurred in the core itself. This was generally true in all of the samples tested.

Thermal-Cycling Tests

An indication of the ability of the clad sheet to withstand rapid changes in temperature was obtained by electrically heating narrow ribbons of the composite sheet and air quenching. The strips of roll-clad sheet, 1/8 in. wide and 6 in. long, were thermally cycled between 500 F and 1500 F, in a helium atmosphere, at the rate of 2 cycles per min. The temperature was measured by means of 36-gage Chromel-Alumel thermocouples spot welded at the center of the strip. After cycling, the specimens were

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sectioned and examined metallographically for evidence of bond failure and cracking in the core. No cracking or bond failure was observed in samples with austenitic matrices, but severe cracking occurred in the pure-iron matrix.

Corrosion Resistance

The corrosion resistance of cladding and core in static water at 5000 psi and 1350 F was investigated also. Small coupons of the various sheets were sheared from the rolled strip and tested with the core exposed at the edges for a 2-week period. The extent of corrosion was determined by sectioning and examining the sheet metallographically at the end of the test. Figure 3 shows the extent of the corrosion. Only the iron matrix was significantly attacked. All of the alloy matrices were quite resistant and showed only slight attack.

DISCUSSION OF RESULTS

The properties of the 0.020-in.-thick roll-clad sheet are dependent not only on the processing variables but also on the composition of the core matrix, the quantity of oxide in the core, and the size and distribution of this oxide in the matrix. These factors are interrelated.

Composition of Core Matrix

The composition of the core matrix is the most significant factor affecting the strength and ductility of clad sheet containing 25 to 30 w/o UO_2 . Table 3 shows the transverse tensile strength and the results of metallographic examination on a series of similarly fabricated clad sheets.

In these samples, three types of core matrices were investigated, and, in addition, the size of the UO_2 was varied. Each matrix composition was roll clad with 0.006 in. of Type 347 stainless steel to form a sandwich-type sheet 0.020 in. in total thickness. The powder-metal-plus-oxide cores were prepared by cold pressing and sintering 4 hr at 2200 F. After jacketing, the sintered compacts were hot rolled to 0.026-in.-thick sheet, according to the rolling schedule given in Table 2. Most of the samples were rolled at 2200 F, but a few of the high-alloy samples were rolled at 2300 F. The hot-rolled sheet was pickled and cold-rolled to 0.020-in. final thickness. All of the sheets were annealed 1/2 hr at 1850 F prior to

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N6007

Matrix: 25 w/o UO_2 in 100 w/o Iron

N6010

Matrix: 25 w/o UO_2 in Iron Plus 18 w/o Chromium

N6007

Matrix: 25 w/o UO_2 in Iron Plus 18 w/o Chromium Plus 9 w/o Nickel

N6010

Matrix: 30 w/o UO_2 in Iron Plus 22 w/o Chromium Plus 12 w/o Nickel

N6011

Matrix: 30 w/o UO_2 in Iron Plus 25 w/o Chromium Plus 20 w/o Nickel

N6008

Matrix: 25 w/o UO_2 in Type 302 Stainless Steel

N6009

Matrix: 25 w/o UO_2 in Type 316 Stainless Steel

N6008

Matrix: 25 w/o UO_2 in Type 347 Stainless Steel

Magnification, 150X, As Polished

FIGURE 3. CORROSION SPECIMENS OF TYPE 347-CLAD FUEL PLATES

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TABLE 3. PROPERTIES OF STAINLESS STEEL-CLAD, STAINLESS STEEL-PLUS- UO_2 -CORED FUEL SHEET^(a)

Sample	Matrix Composition	UO_2 in Matrix, w/o	Oxide-Particle-Size Range, microns	Transverse Tensile Strength, psi	Results of Metallographic Examination
364	Electrolytic iron	25	<53	25,400	No stringers, uniform distribution of oxide, good bond
368(b)	Ditto	"	<53	31,900	Ditto
372	"	"	<44	24,300	"
373	"	"	<44	23,200	"
375	"	"	<3	33,100	"
376(b)	"	"	<3	31,000	"
379	Prealloyed Type 347	"	<53	21,000	Some stringers of oxide, good bond
383	Ditto	"	<53	16,350	Ditto
387	"	"	<44	24,600	"
388	"	"	<44	22,000	"
391	"	"	<3	20,200	Some stringers of oxide, fine particles agglomerated, good bond
392(b)	"	"	<3	22,900	Ditto
443(b)	"	"	7-44	28,100	Some stringers of oxide, good bond
474(b)	"	30	"	24,300	Ditto
478	"	"	"	25,400	"
479	"	"	"	24,200(c)	"
480	"	"	"	24,100(c)	"
450	"	25	44-53	11,200	"
451	"	"	"	15,600	"
452	"	"	"	18,300	"
395	Prealloyed Type 302	"	<53	27,300	Some stringering of oxide, good bond
399(b)	Ditto	"	<53	23,200	Ditto
404	"	"	<44	26,800	"
405	"	"	<44	25,500	"
407	"	"	<3	30,000	"
408(b)	"	"	<3	26,500	"
444	Prealloyed Type 302B	"	7-44	27,300	"
446	Ditto	"	"	30,400	"
447	Prealloyed Type 316	"	"	27,800	Slight stringering of oxide, good bond
449	Ditto	"	"	29,300	Ditto
453	Elemental 18 w/o Cr, bal. Fe	"	44-53	31,200	No stringers, good bond, few isolated Cr particles

TABLE 3. (Continued)

Sample	Matrix Composition	UO ₂ in Matrix, w/o	Oxide-Particle-Size Range, microns	Transverse Tensile Strength, psi	Results of Metallographic Examination
454	Elemental 18 w/o Cr, bal. Fe	25	44-53	30,500	No stringers, good bond, few isolated Cr particles
455	Ditto	"	"	28,100	Ditto
456	"	"	7-44	22,900	"
458	"	"	7-44	26,300	"
411	"	"	<53	29,200	"
412	"	"	<53	28,400	"
419	"	"	<44	30,100	"
422	"	"	<3	29,600	No stringers, good bond, numerous isolated Cr particles
423	"	"	<3	33,300	Ditto
424	"	"	<3	31,900	"
427	Elemental 18 w/o Cr, 9 w/o Ni, bal. Fe	"	<53	31,800	Slight stringering of oxide, good bond, few isolated Cr particles
431	Ditto	"	<53	18,200	Ditto
433	"	"	<53	24,200	"
435	"	"	<44	23,700	"
436	"	"	<44	24,800	"
438(b)	"	"	<3	26,500	Slight stringering of oxide, good bond, numerous isolated Cr particles
439	"	"	<3	27,200	Ditto
440	"	30	7-44	21,700	Slight stringering of oxide, good bond
459	Elemental 22 w/o Cr, 12 w/o Ni, bal. Fe	"	"	26,000	Ditto
462	Ditto	"	"	23,000	"
464	"	"	"	21,400	"
465	"	"	"	25,000(c)	"
466	"	"	"	23,600(c)	"
467	Elemental 25 w/o Cr, 20 w/o Ni, bal. Fe	"	"	21,600	"

TABLE 3. (Continued)

Sample	Matrix Composition	UO ₂ in Matrix, w/o	Oxide-Particle-Size Range, microns	Transverse Tensile Strength, psi	Results of Metallographic Examination
468	Elemental 25 w/o Cr, 20 w/o Ni, bal. Fe	30	7-44	23,600	Slight stringering of oxide, good bond
469	Ditto	"	"	20,400	Ditto
472	"	"	"	22,600(c)	"
473	"	"	"	22,800(c)	"

(a) Hot rolled at 2200 F except as noted, cladding thickness 0.006 in. of Type 347 stainless steel; core thickness 0.008 in.

(b) Average of two tests.

(c) Hot rolled at 2300 F.

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testing. Figures 4 through 7 show the structures obtained with the several matrices and oxide-particle-size ranges.

Distribution and Size of Oxide

The distribution of oxide in the pure iron and the 18 w/o chromium alloy matrices was quite uniform; these matrices consistently yielded the highest transverse tensile strength. The size of the oxide apparently had no significant effect on the strength of the 18 w/o chromium alloy matrix containing 25 w/o of oxide. There was some tendency for the extremely small oxide particles, < 3 microns, to collect around isolated chromium particles, but the strength of the core was not affected. In pure iron, the use of < 3-micron oxide resulted in the highest strength.

The austenitic matrices prepared from elemental powders had lower strength than the ferritic matrices, and there was no significant increase in strength with increasing chromium or nickel content. The distribution of the oxide in these matrices was not so uniform as in the iron or 18 w/o chromium alloy matrices. There was a slight tendency for the oxide to form stringers in the direction of rolling, although this tendency was not so pronounced as in prealloyed cores.

The size of the oxide had no consistent effect on the strength of the 18 w/o chromium - 9 w/o nickel alloy core. Although there was some agglomeration of the < 3-micron oxide around isolated chromium particles in this matrix, the strength of the core was not reduced.

The prealloyed Types 302, 302B, and 316 cores had strengths comparable to those of cores fabricated from the elemental powders. Varying the oxide particle size in a prealloyed Type 302 matrix had no effect on the transverse strength of the core.

Varying the oxide size in a Type 347 matrix, however, caused a marked change in the strength of the core. Only the 5- to 44-micron particles yielded high-strength cores. Both the coarser and finer size ranges of oxide produced sheet with a much lower transverse strength.

The < 3-micron oxide agglomerated during fabrication and the resulting structure was similar to that produced with initially coarser oxide particles.

The tendency for the oxide to form stringers in the direction of rolling was more pronounced in all of the prealloyed matrices than in the elemental-powder matrices.

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100X

As Polished

N2128

Particle Size: Less Than 44 Microns

100X

As Polished

N2129

Particle Size: Less Than 1 Micron

FIGURE 4. STRUCTURE OF CLAD SHEET WITH A CORE CONTAINING 25 w/o UO_2
IN A MATRIX OF ELECTROLYTIC IRON

Particle Size of Oxide as Indicated

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100X

As Polished

N2141

Particle Size: Less Than 44 Microns

100X

As Polished

N911

Particle Size: Less Than 1 Micron

FIGURE 6. STRUCTURE OF CLAD SHEET WITH A CORE CONTAINING 25 w/o OF UO_2 IN A MATRIX OF ELEMENTAL 18 w/o CHROMIUM-9 w/o NICKEL-BAL. IRON

Particle Size of Oxide as Indicated

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27

100X

As Polished

N2154

Particle Size: 7 to 44 Microns

100X

As Polished

N2132

Particle Size: Less Than 1 Micron

FIGURE 7. STRUCTURE OF CLAD SHEET WITH A CORE CONTAINING 25 w/o UO_2
IN A MATRIX OF PREALLOYED TYPE 347 STAINLESS STEEL

Particle Size of Oxide as Indicated

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The pure iron and also the 18 w/o chromium alloy matrices had greater bend ductility than any of the austenitic matrices. Sound bends with a radius of 1/64 in. could be made in the sheet with ferritic cores containing 25 w/o of UO_2 . Sheet with prealloyed Type 347 and elemental 18 w/o chromium - 9 w/o nickel alloy matrices containing 25 w/o of UO_2 could not be bent over radii smaller than 1/32 in. without cracking the core.

Although the strength and ductility of the iron and the 18 w/o chromium alloy cores were good, their resistance to thermal cycling was poor. Figure 8 shows the severe cracking observed in an iron-matrixed sample cycled 1000 times between 500 and 1500 F at the rate of 2 cycles per min. Only about 250 such cycles were required to produce the first visible evidence of failure in this core. When the maximum temperature of the cycle was reduced to 1300 F, the number of cycles required to produce cracking was increased to approximately 1000.

The 18 w/o chromium alloy core was more resistant to cracking than the pure-iron core; but, as shown in Figure 9, cracking had started in this core after 1000 cycles between 500 and 1500 F. The cracking occurred only in the core, and there was no evidence of separation between cladding and core.

All of the austenitic matrices had excellent resistance to thermal cycling. No evidence of cracking was observed in any of these samples after 1000 cycles between 500 and 1500 F.

Quantity of Oxide

A second series of samples was rolled to investigate the effect of the quantity of UO_2 in the matrix on the strength and ductility of the core. Clad sheets were fabricated with pure-iron and elemental 18 w/o chromium - 9 w/o nickel matrices containing 20, 25, 30, and 40 w/o of UO_2 . Prealloyed Type 347 cores containing 40, 45, 50, and 60 w/o of UO_2 also were fabricated. The particle size of the oxide in the elemental 18 w/o chromium - 9 w/o nickel matrix was 7 to 44 microns, and the 0- to 58-micron size range was used in the iron and the Type 347 cores.

The sintered powder-metal compacts were jacketed and then cross rolled to 50 per cent reduction at 2200 F. The remainder of the hot rolling was in the longitudinal direction at a temperature of 1850 F. After pickling, the sheets were cold rolled from approximately 0.026 to 0.020 in. and annealed 1/2 hr at 1850 F. The intended cladding thickness was 0.006 in. with a core 0.008 in. thick.

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100X

As Polished

N5295

FIGURE 8. CRACKS IN IRON MATRIX AFTER 1000 CYCLES BETWEEN 500 AND 1500 F

100X

As Polished

N5294

FIGURE 9. CRACKS IN 18 w/o CHROMIUM-BAL. IRON MATRIX AFTER 1000 CYCLES BETWEEN 500 AND 1500 F

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There was a marked decrease in the transverse strength of these sheets with increasing oxide content. The iron core had slightly higher strength than the 18 w/o chromium - 9 w/o nickel core, but both cores showed a similar drop in strength with increasing oxide content. Figure 10 shows the effect of increasing oxide content on the transverse strength.

The prealloyed Type 347 cores containing 40 w/o and more of UO_2 were extremely weak. Metallographic examination of these samples showed that the oxide formed large stringers and laminations.

The ductility of the cores also decreased with increasing oxide content. With 20 and 25 w/o of UO_2 in an iron matrix, a 1/64-in. -radius bend could be made in the clad sheet without cracking the core. With 30 and 40 w/o of UO_2 in the matrix, cracking occurred in 1/64-in. -radius bends, but 1/32-in. -radius bends were sound.

The minimum bend radius of the 18 w/o chromium - 9 w/o nickel alloy core containing 20 w/o UO_2 was 1/32 in. The ductility decreased with increasing oxide content until at 40 w/o of UO_2 , the minimum bend radius for sound bends was 3/32 in.

The core of prealloyed Type 347 steel containing 40 w/o UO_2 also could be bent around a 3/32-in. radius without cracking. The samples with 60 w/o UO_2 , however, cracked at 1/8-in. radius, the maximum-radius bend attempted. All of the samples containing more than 40 w/o UO_2 were quite brittle, and the core tended to split in the plane of the sheet.

CONCLUSIONS

A satisfactory method of producing stainless steel clad, stainless steel-plus- UO_2 fuel sheet was developed in which a cold-pressed and sintered powder-metal compact was jacketed by the picture-frame technique and hot rolled at 2200 F.

Of the several matrix compositions investigated, only the austenitic alloys did not crack in thermal-cycling tests. Ferritic matrices of pure iron and iron plus 18 w/o chromium had the best bend ductility and strength, but both of these matrices cracked when thermally cycled between 500 and 1500 F.

The 18 w/o chromium - 9 w/o nickel alloy matrix prepared from elemental powders had better fabricating characteristics than prealloyed austenitic alloys. The pressing characteristics of the powder and the green strength of the compacts were superior to those of the prealloyed

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FIGURE 10. EFFECT OF OXIDE CONTENT ON TRANSVERSE TENSILE STRENGTH OF CLAD SHEET

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stainless steel powders. There was also less tendency toward the formation of stringers of the oxide in matrices prepared from elemental powders.

The size of the UO_2 had little effect on the transverse strength of clad sheet prepared from elemental powders. In the prealloyed Type 347 matrix, however, the intermediate-size oxide, 7 to 44 microns, yielded the highest strength cores.

The transverse strength of the clad sheet decreased rapidly with increasing amounts of oxide in the core. The effect of oxide content was similar in pure iron and elemental 18 w/o chromium - 9 w/o nickel matrices. The latter matrix, containing up to 40 w/o UO_2 in the 0.008-in.-thick core, had considerable ductility, but even with only 20 w/o of oxide, the ductility was sufficiently reduced to make $1/2T^*$ bends impractical.

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* Where T = sheet thickness.

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