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Fabrication Technology for ODS Alloy MA957

M. L. Hamilton

D. S. Gelles

R. J. Lobsinger*

M. M. Paxton*

and

W. F. Brown*

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* Originally with Westinghouse Hanford Company

Pacific Northwest Laboratory
Richland, Washington 99352

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MA957 FABRICATION TECHNOLOGY

I. SUMMARY

A successful fabrication schedule has been developed at Carpenter Technology Corporation for the production of MA957 fuel and blanket cladding. Difficulties with gun drilling, plug drawing and recrystallization were overcome to produce a pilot lot of tubing. This report documents the fabrication efforts of two qualified vendors and the support studies performed at WHC to develop the fabrication schedule.

II. INTRODUCTION

MA957 is an oxide dispersion strengthened (ODS) ferritic alloy developed by the International Nickel Company (INCO) for use in liquid metal reactors.(1) The oxide dispersion, in this case yttria, is intended to provide the high temperature strength lacking in other swelling resistant ferritic alloys. The alloy is produced by a patented process known as mechanical alloying, which is a powder metallurgy milling process which distributes the alloy ingredients homogeneously on a very fine scale. Alloy powders are blended in an attritor and subsequently consolidated by hot extrusion in an evacuated steel can. The resulting wrought bar is hot worked and then cold worked to its final shape.

While INCO's patent claims that the alloy is readily fabricable, the minimal amount of fabrication technology data generated by INCO are proprietary. No commercial vendor had any experience in the fabrication of the alloy. In order to use MA957 for cladding in the DSF-1 and ABA-9 assemblies, it was therefore necessary for Westinghouse Hanford Company to develop a fabrication path with a certified manufacturer and specify the range of acceptable processing parameters for the production of reactor grade tubing.

Bar stock was procured from Wiggin Alloys Limited, a subsidiary of INCO, in October, 1985. Fabrication development studies were performed at both Superior Tube Company (STC) and Carpenter Technology Corporation (CarTech). Metallurgical studies performed at Westinghouse Hanford Company (WHC) in support of the fabrication development effort included chemical and microstructural characterization, cold working and recrystallization studies, nondestructive testing, and pulse magnetic welding.

CarTech won the procurement contract and is proceeding with the fabrication of the cladding required for DSF-1 and ABA-9. This document summarizes the current status of the fabrication technology development program, describing both the offsite fabrication development effort and the metallurgical studies performed at WHC to support the program.

III. ALLOY CHARACTERIZATION: COMPOSITION AND MICROSTRUCTURE

The nominal composition specification for MA957 is provided in Table 1. The alloy is a ferritic steel strengthened at high temperatures by a yttria dispersion. Titanium and molybdenum are added to improve strength, ductility and oxidation resistance.

Numerous chemical overcheck analyses were performed on four heats of the alloy at two different offsite laboratories. The average and the range of the results of the overchecks are also given in Table 1. A complete record of the overcheck analyses is provided in Appendix A. It is evident in Table 1 that the major alloy components (Cr, Ti, Mo and Y_2O_3) are close to their nominal compositions. There is some variability in the determinations of oxygen, manganese and phosphorus. There is also a large amount of aluminum present, which is manifested as alumina stringers. It is believed that these stringers are detrimental to the overall behavior of the alloy. The presence of the aluminum has been attributed to the ferrochrome powder with which the chromium is added to the alloy. Several percent alumina were present in the powder. It is recommended that further development of the alloy include the elimination of aluminum from the alloy through more stringent limits on the purity of the starting metal powders.

Typical examples of the microstructure of the alloy are shown in Figure 1. Figures 1a and 1b show the transverse and longitudinal structure at low magnification using optical metallography and Figures 1c and 1d show the same regions at higher magnification. The structure is highly anistropic with equiaxed grains in the transverse direction but with highly elongated grains in the longitudinal or working direction. This anisotropy was shown to have a significant effect on the fabricability of the alloy, as will be discussed in more detail later. Figure 1 also reveals many titanium carbide precipitate particles and several alumina stringers. The carbides are believed to be titanium and molybdenum carbides, where the titanium and molybdenum were added intentionally to prevent the formation of chromium carbide, a phase responsible for grain boundary embrittlement or sensitization. Figure 2 shows the structure at higher magnification using transmission electron microscopy. The grain structure consists of well defined subgrain boundaries pinned by

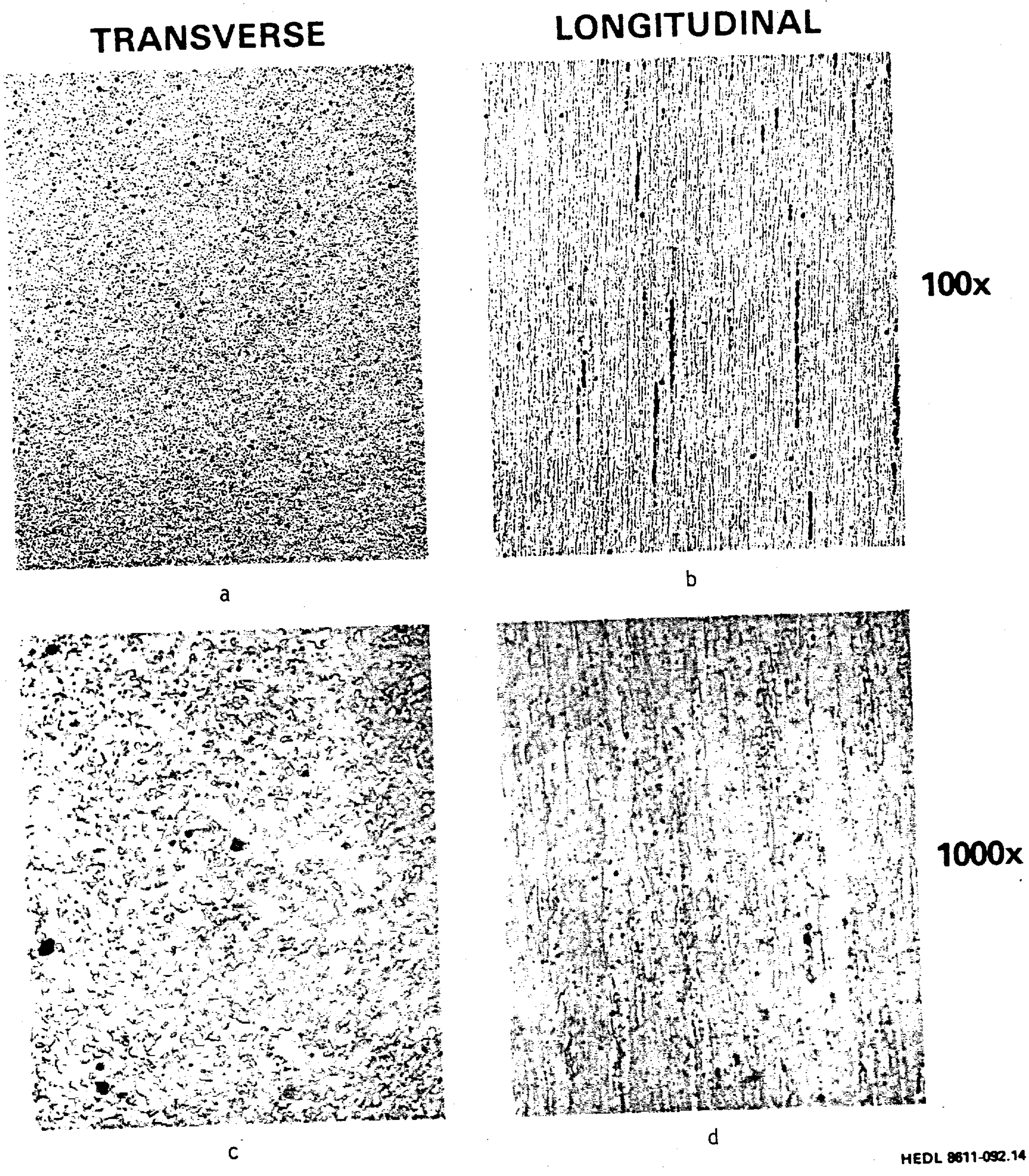


FIGURE 1. Microstructure of As-Received MA957 Bar Showing Optical Metallography of Transverse and Longitudinal Sections at (a,b) 100x and (c,d) 1000x

TABLE 1

COMPOSITION OF MA957

ELEMENT	WEIGHT PERCENTAGE AVERAGE	RANGE	NOMINAL
Cr	13.87	13.49 - 14.19	14
Ti	1.05	0.95 - 1.38	0.9
Mo	0.30	0.28 - 0.32	0.3
$Y(Y_2O_3)$	0.22	0.19 - 0.28	0.25
O	*	0.006 - 0.240	-
C	0.014	0.012 - 0.017	-
Mn	**	0.05 - 0.12	-
Si	0.04	0.02 - 0.07	-
P	***	0.004 - 0.030	-
Ni	0.13	0.10 - 0.15	-
Al	0.10	0.055 - 0.17	-
S	0.006	0.004 - 0.006	-
Fe	Bal	Bal	Bal

* Two sets of values were present, one with a range of 0.006 to 0.02 weight percent oxygen and an average of 0.014 weight percent oxygen, and one with a range of 0.21 to 0.24 weight percent oxygen and an average of 0.22 weight percent oxygen.

** Two distinct sets of values were present, one with a range of 0.05 - 0.06 weight percent manganese and an average of 0.06 weight percent manganese, and one with a range of 0.11 to 0.12 weight percent manganese and an average of 0.11 weight percent manganese.

*** Two distinct sets of values were present, one at < .005 weight percent phosphorous and one with a range of 0.011 to 0.030 weight percent phosphorous and an average of 0.017 weight percent phosphorous.

titanium carbide particles. The yttria particles are distributed uniformly within the grains as particles less than 50 Angstroms in diameter. It is this microstructure which provides the high temperature strength of the alloy.

FIGURE 2. Microstructure of As-Received MA957 Bar Showing a Longitudinal Section Using Transmission Electron Microscopy at 300,000x.

IV. METALLURGICAL SUPPORT STUDIES

Two factors controlled the selection of the final fabrication path: the need to minimize the cost of fabrication and the need to maintain the microstructure described above. The desire to minimize the cost of fabrication requires that the number of reductions be minimized, hence the reductions must be taken at the maximum level possible. The need to maintain the existing microstructure limits the temperature at which interpass anneals can be performed.

Several WHC studies demonstrated that the working behavior of the alloy was highly directional, with transverse ductility significantly larger than longitudinal ductility (orientations are given with respect to the working direction and the direction of grain elongation).[2] An example of this is given in Figure 3, which shows the change in hardness as a function of reduction in thickness as well as the maximum reduction level obtained in a longitudinal and a transverse section of bar prior to cracking. Longitudinal and transverse working produce similar increases in hardness, although the longitudinal section failed at a lower reduction than the transverse section. The differences in deformation limit with orientation are not, therefore, due to differences in the work hardening rate but are rather due to strain limits which are orientation dependent. The geometry of the tubing requires longitudinal working of the tube hollows, limiting each reduction to about 15 or 20%.

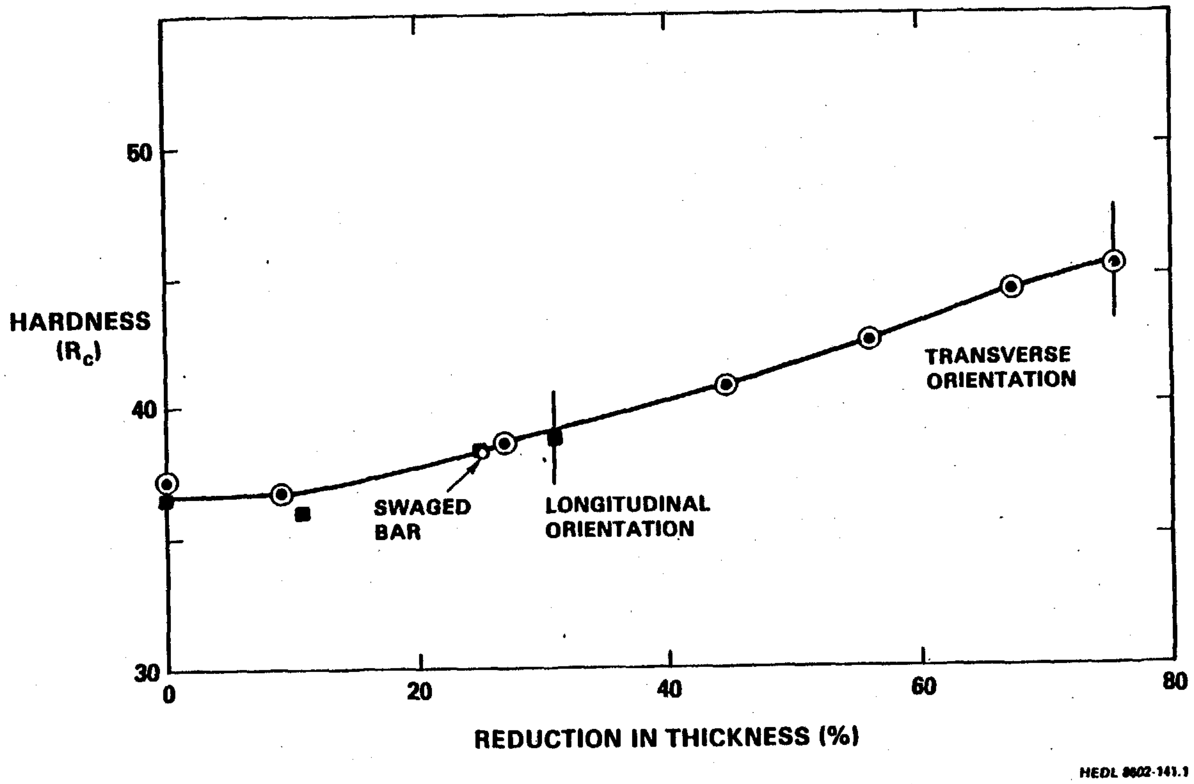


FIGURE 3. The Effect of Cold Rolling on the Hardness of MA957 as a Function of Reduction in Thickness. The Last Measurement for Each Section Indicates the Point at which Cracking Initiated.

Interpass anneals are required to relieve the stresses induced by working in order to allow continued reductions. The higher the stress relief temperature, the more recovery occurs and the larger the subsequent reductions. Laboratory experiments and tube drawing tests demonstrated that INCO's recommended annealing temperature of about 800°C was too low, causing insufficient recovery of the microstructure and subsequent cracking with additional processing. Two studies have demonstrated that the desired microstructure cannot be regenerated once eliminated by recrystallization during thermal annealing,[2,3] putting an upper limit on the annealing temperature. The final processing window determined for successful fabrication is shown in Figure 4, indicating that both cracking and recrystallization can be avoided if cold work levels are held to about 15% and annealing temperatures are around 1000°C.

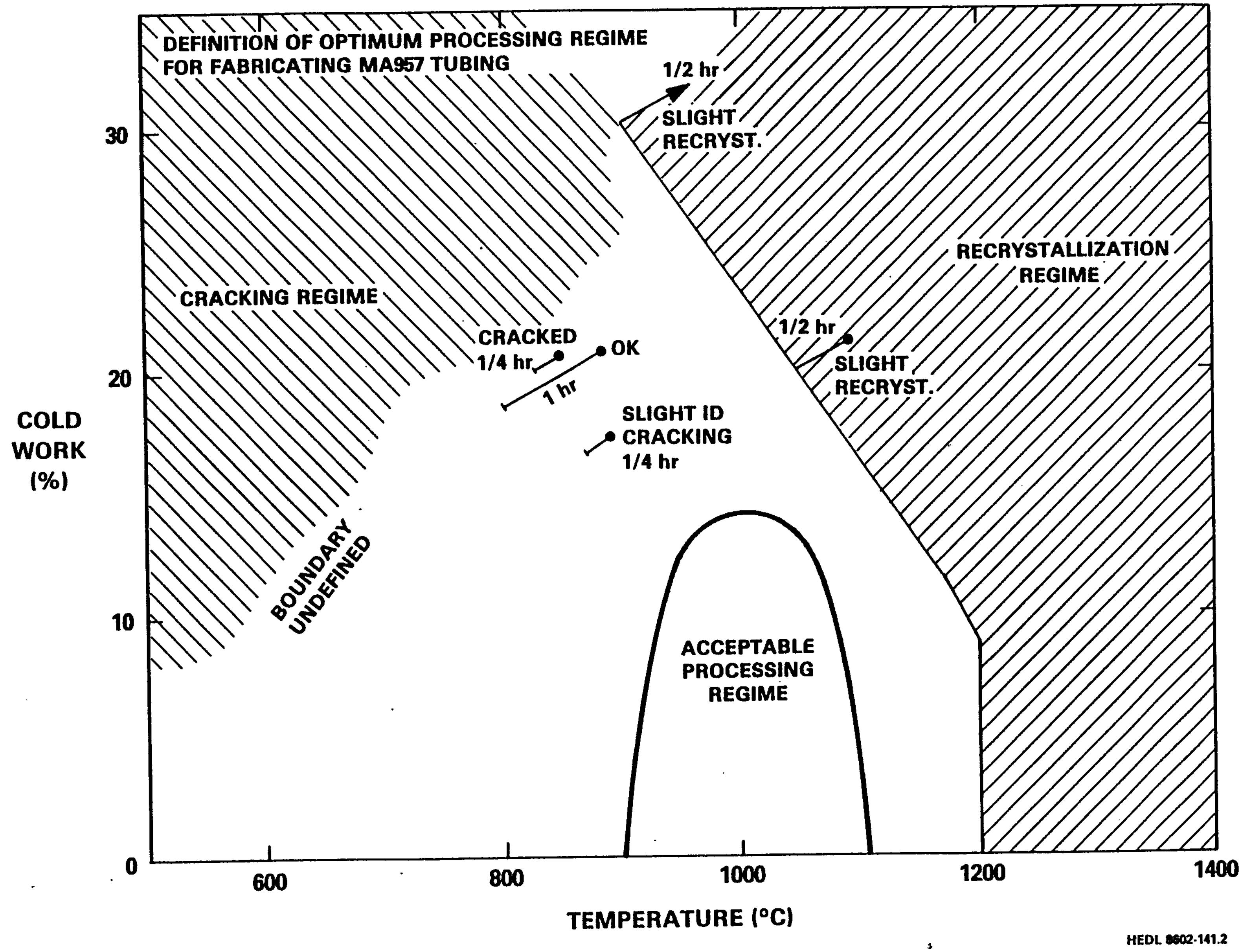


FIGURE 4. Definition of the Optimum Processing Regime for Fabricating MA957 Tubing.

V. FABRICATION DEVELOPMENT EFFORTS AT WHC

Fabrication efforts were conducted on MA957 at WHC to provide rod and tubing for mechanical properties testing as well as to provide input that would assist qualified cladding suppliers in producing commercial quantities of fuel and blanket cladding. These efforts contributed significantly to the establishment of the processing regime window described in the previous section.

A bar of MA957 was successfully swaged from one inch in diameter to about a quarter inch in diameter using an interpass anneal at 1050°C according to the reduction schedule given in Table B1 in Appendix B. The hardness decreased significantly during reduction as a result of secondary recrystallization. Reduction of a tube hollow (Table B2) which had been partially processed at 1050°C and exhibited secondary recrystallization was continued with a drop in annealing temperature to 800°C on INCO's recommendation. The tube hollow cracked after three anneals at 800°C, demonstrating that the optimum stress relief temperature was between 1050 and 800°C.

On the basis of this experience, additional fabrication of rod and tubing was initiated at WHC using 15% reductions and 825°C anneals as a precursor to the commercial fabrication effort. A second bar was successfully swaged from one inch in diameter to 0.265 inches in diameter (Table B3). The annealing temperature was increased to 875°C after the first three reductions due to increases in hardness. Pressurized tube specimens were fabricated for MOTA irradiation from this rod.

Another batch of tubing was subsequently made at WHC by rod drawing from a starting size of 0.9 x 0.485 inches to a final size of 0.230 x 0.200 inches (Table B4). All reductions were approximately 15%, and all anneals were at about 1000°C. The initial hardness of the tube hollow, R_C 31.5, increased to R_C 38 (after an anneal) after only a few reductions and gradually decreased to R_C 35 by the final reduction. Stress rupture tests are being performed on samples sectioned from this batch of tubing.

VI. VENDOR FABRICATION: STC

A fabrication development contract was placed with STC in Collegeville, PA for the fabrication of 0.270 x 0.226 inch cladding from starting bar provided by WHC. STC selected a reduction sequence using rod drawing followed by two roll derodding. Initial cold pointing operations resulted in cracking of the point. This was resolved by heating the nose and pointing at red heat, a technique with which WHC also had success. Significant increases in hardness were produced using a annealing temperature of 875°C, selected initially on the basis of prior WHC efforts. Increasing the annealing temperature to 900°C did not ameliorate the problem. After ten draws, hardness had increased from about 34 to about 42 on the Rockwell C scale with no recrystallization observed. The lot was divided into two pieces and the processing temperature of the second lot was increased to 1000°C to increase the probability of success. Fabrication continued on both lots to completion and metallographic examination of both lots revealed a similar structure and hardness. Eight feet of finished tubing (four in each lot) required 17 rod draws and one plug draw. The plug draw is performed last to ensure that dimensional tolerances are met. Stress rupture tests performed on the tubing produced by STC demonstrate excellent high temperature strength, superior to that of HT-9 above temperatures of about 650°C.

VII. VENDOR FABRICATION: CARTECH

An identical fabrication development contract was placed with CarTech in El Cajon, CA. A follow-on requirement was included on the basis of a low bid for a best efforts performance for production quantities of fuel and blanket cladding. CarTech initially elected to use plug draws in the belief that this would be a more conservative approach, since they felt that the only means they had of derodding the tube hollows was to use a straightener, which it was believed would crack the tubing. The combination of the plug draws and the 875°C annealing temperature created serious fabrication difficulties, including the breaking off of the point and the appearance of significant transverse cracks. Increasing the annealing temperature to 900 and then to 925°C did not help soften the material, which had increased to R_C 42. After machining away the cracks on both the inner and outer diameters, a successful rod draw was completed, but the tube split full length during the derodding operation.

A portion of the bar stock intended for the production of cladding was used in CarTech's second unsuccessful attempt to plug draw tubing. Two lots were run at annealing temperatures of 1000 and 1100°C at WHC's request in order to bracket a probable range of feasibility. CarTech declined to consider rod draws on the basis of equipment limitations and the earlier derodding experience. The lower temperature lot was halted after cracking problems appeared. The upper temperature lot exhibited a new problem: recrystallization softened the tubing sufficiently that the drawing forces induced local yielding as the tubes were being drawn, producing a series of convolutions on the tube surfaces. Warm working at a temperature below about 150°C did not alleviate the problem, as the elevated temperature caused the lubricant to break down, resulting in significant plug chatter.

It was evident that the microstructure and therefore the fabrication of MA957 is very sensitive to the combination of drawing method and annealing temperature, since rod draws and 900°C were successful at STC while plug draws and 1000°C failed at CarTech. The failure of plug drawing was attributed by WHC to the sensitivity of the alloy to the large tensile loads produced by this method, exacerbated by the nonoptimum die angles used by the vendor. CarTech therefore initiated a die angle optimization effort to reduce the draw pressure and established the cold working capability of the alloy by measuring the springback of bar drawn through a range of reduction sequences. The third run was approved on the basis of these studies.

Preparation of the additional bars for the third run revealed that excessive eccentricity was sustained during the gun drilling of the production bars supplied by INCO, a problem which had not existed earlier. Neither heat-to-heat variations nor residual stresses accounted for the difficulties, nor were they solved by using alternate tool designs. Some evidence suggested that the bar hardness varied throughout its length, affecting the drilling operation. Comparative work with 316 stainless steel demonstrated that the basic process was acceptable and that the difficulty lay with the alloy itself. Additional work on the gun drilling problem continued during the third run, culminating in the establishment by CarTech of satisfactory proprietary parameters for the gun drilling operation.

The third run evaluated the viability of both rod and plug drawing in the initial reduction operations. Interpass anneals were performed at 1000°C for both rod and plug drawn material. Both the rod and plug draw operations were performed using the optimized die angles established by the vendor which successfully reduced the required draw forces. Plug draws, however, were discontinued after the third draw when the rod holding the plug broke. Although the lower die angle reduced the draw bench pressures and the strain hardening of the tubing, it also increased the frictional forces within the die, leading to the rod failure. No unexpected problems appeared during rod drawing operations. Derodding was performed using shaped rolls to expand the tubing off the mandrel. A crack induced during a pointing operation propagated a short distance during an intermediate draw; this problem was eliminated in subsequent draws by performing a dye penetrant examination after each pointing operation.

The successful completion of the rod draw portion of the third run finished the pilot process required to establish the reference fabrication parameters for the production of fuel and blanket cladding. It required 23 rod draws and a final plug draw to convert the tube hollow to finished 0.270 x 0.226 inch tubing. Hardness of the tubing during the third run is shown in Figure 5 as a function of reduction; it stabilized at a Rockwell C value of about 40.5. Twenty to thirty percent of the microstructure appears to have recrystallized, but this is not expected to have a significant effect on the behavior of the cladding in the operating regime of interest. Stress rupture tests are being initiated to verify this expectation. Gun drilling of the remaining bars is underway and tube reduction is expected to begin shortly. Figure 6 illustrates the microstructure of the tubing produced by WHC, STC and CarTech relative to as-received bar stock.

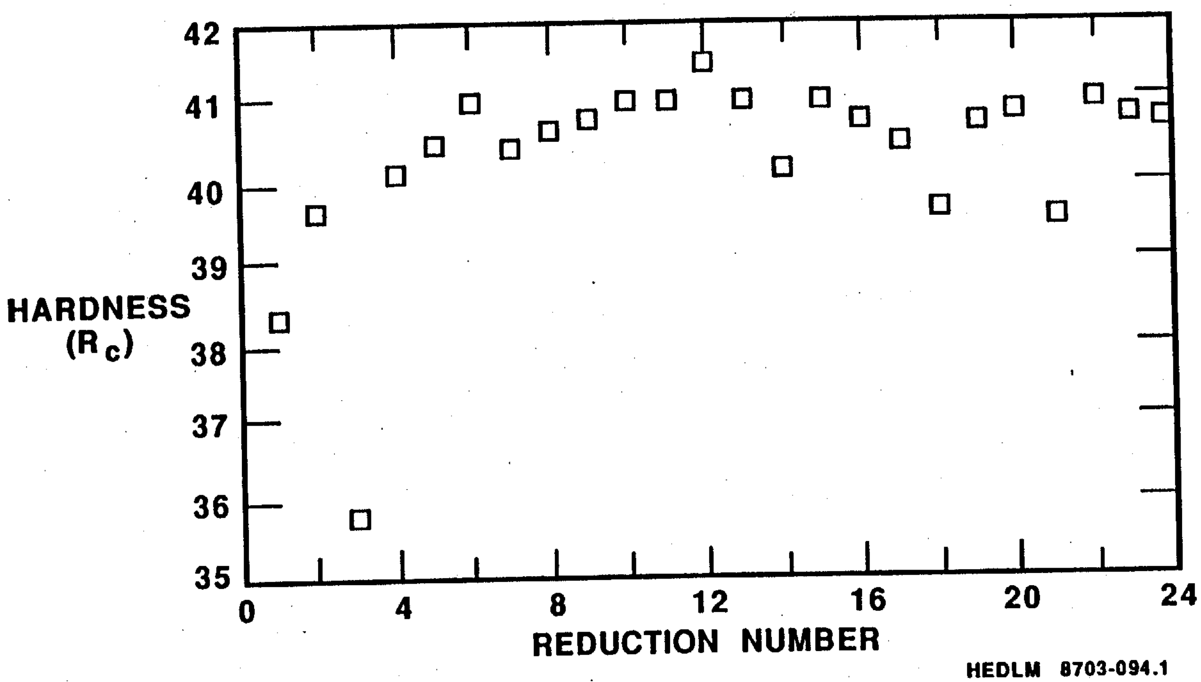


FIGURE 5. Hardness of Tubing Produced at CarTech during Third Run.

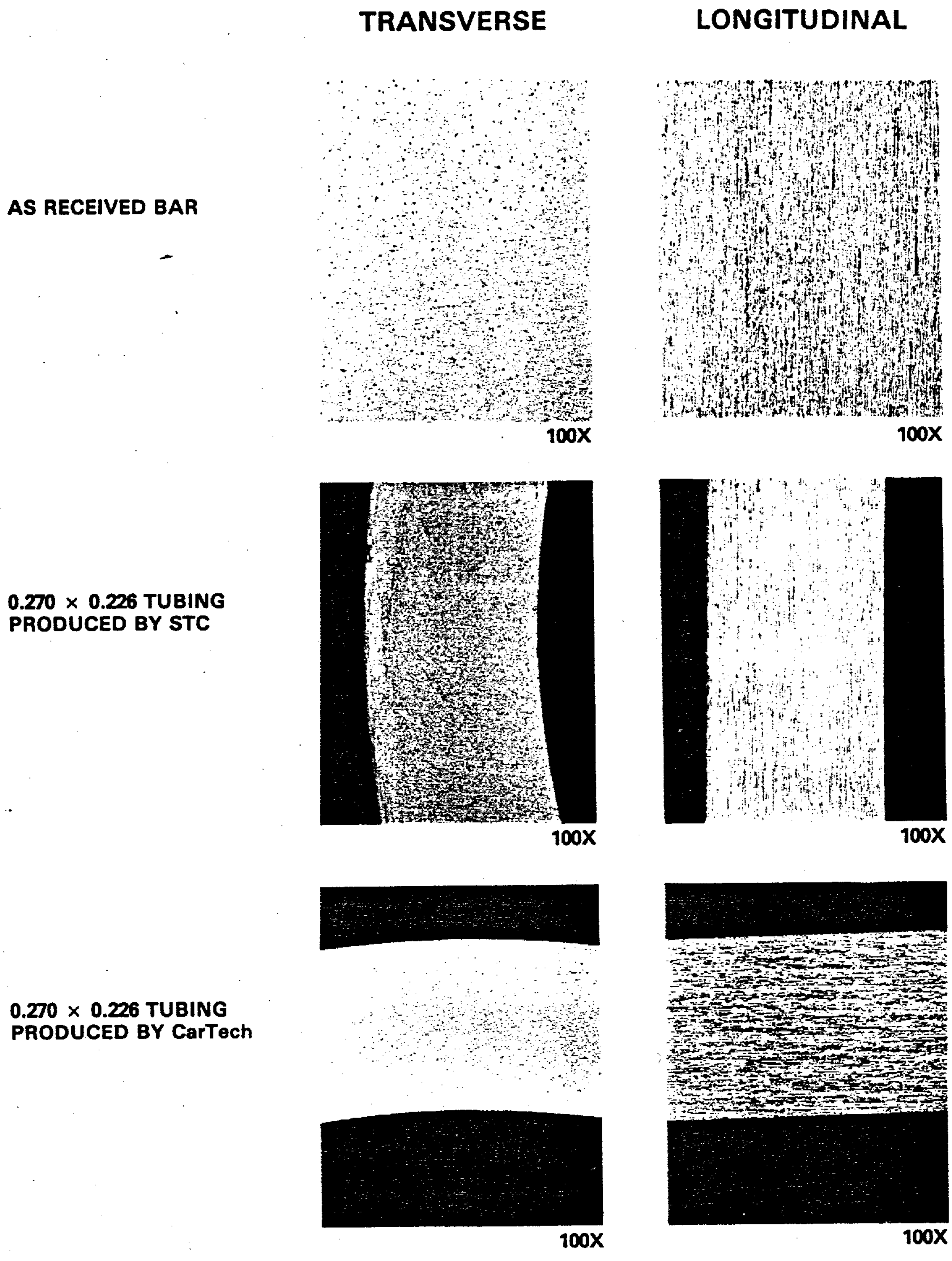


FIGURE 6. Microstructure of As-Received Bar Stock and the Tubing Produced by WHC, STC and CarTech.

VIII. NONDESTRUCTIVE TESTING

Several types of nondestructive evaluations were performed on as-received bar stock to verify the acceptable condition of the starting material. These included ultrasonic velocity and attenuation, eddy current, radiography, thermoelectric and magnetic field determinations. No flaws were detected in any of these determinations nor were there any unexpected signal degradations which could be attributed to microstructural variabilities.

IX. PULSED MAGNETIC WELDING

The oxide dispersion added to strengthen the alloy makes MA957 a very difficult alloy to weld by traditional fusion methods due to the porosity and slag created during the melting process and the inherent weakness of the weld metal following removal of the dispersoid. Pulsed magnetic welding (PMW) has long been used on ferritic HT-9 tubing, and was therefore selected as the technique most likely to be easily adapted for use on MA957 tubing.

The feasibility of PMW has been demonstrated on both MA956 and MA957 tubing, although the optimum weld parameters have not yet been established. MA956 is an ODS alloy similar to MA957 which was used prior to the availability of MA957 tubing. The limited amount of either material available allowed the variation of only one welding parameter, voltage. As shown in Figure 7, good solid state welds can be achieved between MA956 or MA957 tubing and HT-9 endcaps. Tests documented in Appendix C demonstrated that higher energy levels will be required than are used on austenitic stainless steels or HT-9.

When tubing from the pilot lot produced by CarTech is available, prequalification studies will include the following efforts:

1. Develop cladding expanding technique for top end fuel with funnel loading.
2. Determine effects of tubing ID surface condition on welding.
3. Determine effects of PMW on HT-9 end cap heat treatment.

4. Verify end cap design.

5. Determine effects of driver sleeve size on welding.

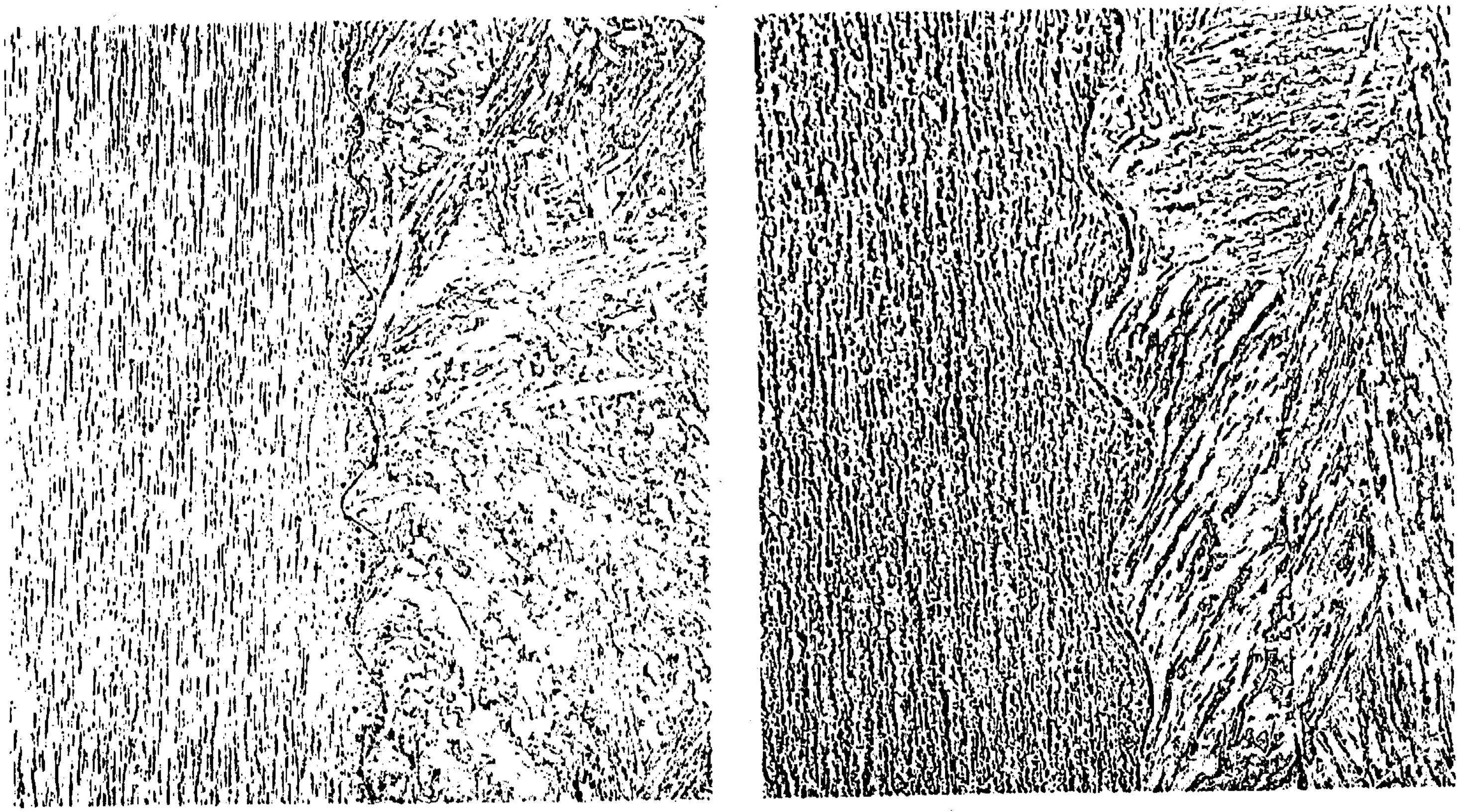
6. Establish a welding parameter envelope and prepare a welding procedure.

7. Qualify procedure in accordance with requirements of the Specification for FFTF Driver Fuel Pins (HEDL-S-0021) and the Test Design Description for the High-Burnup Dispersion-Strengthened Ferritic Fuel Test, DSF-1 (HEDL-TC-2814).

8. Perform burst tests at elevated temperatures to ensure the strength of the welds.

A schedule for these activities is given in Table 2.

MA957 MA956



500X 500X

HEDL 8703-097.2

FIGURE 7. Sound Weld in MA956 and MA957.

TABLE 2

SCHEDULE OF PMW QUALIFICATION ACTIVITIES

	MARCH	APRIL	MAY	JUNE	JULY
Prequalification Studies	———	———	———		
Procedure Qualification			———	———	
Elevated Temperature Tests				———	——— — —

X. REFERENCES

1. J. J. Fischer, U. S. Patent 4,075,010, "Dispersion Strengthened Ferritic Alloy for use in Liquid Metal Fast Breeder Reactors," issued Feb. 21, 1978.

2. M. L. Hamilton, M. M. Paxton, D. S. Gelles, and R. J. Lobsinger, "Development of MA957 Fuel Cladding," (1985) unpublished work available from the authors.

3. D. S. Gelles, T. Rees and M. M. Paxton, "Fabrication Procedure Development of MA957 for Fuel Cladding," (1985) unpublished work available from the authors.

APPENDIX A

COMPOSITION OF MA957

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COMPOSITION OF MA957

Overcheck analyses were performed at Koon-Hall and at CarTech on the four heats of the alloy available. A complete summary of the results of the chemical overcheck analyses is given in Table A1.

TABLE A1

CHEMICAL OVERCHECK ANALYSES ON MA957 BAR STOCK (weight percent)

	Wiggin Certifications				Carpenter Technology Overcheck Certifications						Koon-Hall Overcheck Certifications				
Cast No:	DBB0111	DBB0114	DBB0120	DBB0122	DBB0111	DBB0111	DBB0111	DBB0114	DBB0120	DBB0122	DBB0111	DBB0111	DBB0111	DBB0111	DBB0111
WHC Bar No.:	---	---	---	---	1[3]	2[4]	3[4]	---	---	---	1[4]	1[3]	1[3]	2[4]	3[4]
Cr	14.17	13.59	14.10	14.16	13.84	13.93	13.84	13.49	14.01	14.19	13.95	14.03	13.54	13.57	13.57
Ti	0.99	0.95	1.01	1.02	1.08	0.99	1.00	0.96	1.03	1.03	1.38	1.10	1.04	1.07	1.07
Mo	0.30	0.29	0.31	0.31	0.31	0.29	0.28	0.30	0.31	0.31	0.30	0.31	0.32	0.31	0.31
Y (Y_2O_3)	0.27	0.28	0.27	0.27	NA	0.22	0.22	0.22	0.22	0.22	0.26	0.017[2]	0.19	0.22	0.20
O	0.22	0.24	0.21	0.02	0.006	0.019	0.014	0.22	0.22	0.22	0.012	0.220	0.220	0.220	0.220
C	0.017	0.015	0.013	0.014	0.014	0.016	0.012	0.013	0.016	0.013	0.014	0.015	0.015	0.014	0.015
Mn	NA	NA	NA	NA	0.05	0.05	0.05	0.06	0.06	0.06	NA	NA	0.12	0.11	0.11
Si	NA	NA	NA	NA	0.05	0.05	0.05	0.03	0.03	0.03	0.02	0.04	0.07	0.05	0.05
P	NA	NA	NA	NA	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.030	0.004	0.011	0.011	0.011
Ni	NA	NA	NA	NA	0.13	0.13	0.13	0.10	0.10	0.10	0.15	0.12	0.14	0.15	0.15
B	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<0.005	NA	NA	NA
Al	NA	NA	NA	NA	0.07	0.06	0.06	0.09	0.08	0.07	0.055	0.10	0.16	0.17	0.17
Sn	NA	NA	NA	NA	0.005	0.005	0.005	<0.005	<0.005	<0.005	0.002	<20 ppm	26 ppm	26 ppm	24 ppm
N	0.045	0.045	0.038	0.033	0.039	0.045	0.039	0.051	0.047	0.040	0.046	0.049	0.048	0.048	0.048
Ce	NA	NA	NA	NA	NA	0.02	0.02	0.02	0.02	0.02	NA	NA	NA	NA	NA
S	NA	NA	NA	NA	0.006	0.006	0.006	0.004	0.006	0.004	NA	NA	0.006	0.006	0.006
Cu	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.03	0.02	0.03
Nb + Ta	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.009	0.009	0.009
As	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<0.0001	<20 ppm	5 ppm	3 ppm	2 ppm
Fe	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal

[1] Not Analyzed
[2] Probably a typographical error meant to read 0.20
[3] Quarter-inch diameter rod stock
[4] One-inch diameter bar stock

A P P E N D I X   B

WHC REDUCTION SEQUENCES

APPENDIX B

WHC REDUCTION SEQUENCES

The following tables document some of the reduction sequences used at WHC to produce both rod and tubing. The first table documents the successful reduction of rod roughly a quarter inch in diameter from one inch diameter bar stock. The second table documents the unsuccessful reduction of tubing from the same bar due to the cracking which occurred. The third and fourth tables summarize the production of additional rod and tubing.

TABLE B1

MA957 REDUCTION SEQUENCE BY SWAGING

INITIAL OD (Inches)	FINAL OD (Inches)	REDUCTION IN AREA (%)	SWAGED HARDNESS (R_C)	SUBSEQUENT INTERPASS ANNEAL (°C/minutes)	ANNEALED HARDNESS (R_C)
1.00	0.865	25.0	36.4	1050/13	36.4
0.865	0.754	24.0	36.0	1050/13	35.9
0.754	0.633	29.5	37.8	1050/13	34.5
0.633	0.504	36.7	36.9	1050/13	33.9
0.504	0.438	24.5	35.9	1050/13	31.6
0.438	0.370	28.7	35.2	1050/13	30.5
0.364	0.327	21.9	32.8	1050/13	30.8
0.327	0.295	18.7	33.6	1050/13	-
0.295	0.260	22.3	-	1050/13	-

TABLE B2

MA957 TUBE REDUCTION

INITIAL SIZE OD x ID (Inches)	FINAL SIZE OD x ID (Inches)	REDUCTION IN AREA (%)	SWAGED HARDNESS (R_c)	SUBSEQUENT INTERPASS ANNEAL (°C/minutes)	ANNEALED HARDNESS (R_c)
0.913 x 0.579	0.875 x 0.563	10.0	36.0	1012/13	32.9
0.875 x 0.563*	0.800 x 0.525	18.8	36.2	1050/15	33.2
0.800 x 0.525*	0.760 x 0.500	10.1	35.9	1050/15	35.0
0.760 x 0.500*	0.700 x 0.475	19.3	36.1	800/60	35.4
0.700 x 0.475*	0.650 x 0.450	16.8	36.0	800/15	34.1
0.650 x 0.450*	0.600 x 0.425	18.5	35.0	800/15	**
0.600 x 0.425*	0.550 x 0.400	20.6		***	

* Swaged on mandrel.
** Cracks appeared on ID.
*** Swaged 1/2 tube, stopped due to OD cracks.

TABLE B3

REDUCTION SEQUENCE OF SECOND ROD

INITIAL SIZE (Inches)	FINAL SIZE (Inches)	REDUCTION IN AREA (%)	INTERPASS ANNEAL (°C/Min.)
1.000	0.930	13.5	825/15
0.930	0.870	12.5	825/15
0.870	0.820	11.2	825/15
0.820	0.770	11.8	875/15
0.770	0.720	12.6	875/15
0.720	0.661	15.7	875/15
0.661	0.615	13.4	875/15
0.615	0.593	7.0	875/15
0.593	0.565	9.2	875/15
0.565	0.540	8.7	875/15
0.540	0.515	9.0	875/15
0.515	0.480	13.1	875/15
0.480	0.437	17.1	875/15
0.437	0.412	11.1	875/15
0.412	0.387	11.8	875/15
0.387	0.361	12.9	875/15
0.361	0.334	14.5	875/15
0.334	0.310	13.8	875/15
0.310	0.297	8.2	875/15
0.297	0.281	10.5	875/15
0.281	0.265	11.0	875/15

TABLE B4

SUCCESSFUL REDUCTION OF MA957 TUBING

INITIAL SIZE OD x ID (Inches)	FINAL SIZE OD x ID (Inches)	REDUCTION IN AREA (%)	INTERPASS ANNEAL (°C/Min.)	ANNEALED HARDNESS (DPH)
0.902 x 0.485	0.875 x 0.476	6.8	1000/15	-
0.875 x 0.476	0.821 x 0.470	16.2	1000/15	-
0.821 x 0.470	0.800 x 0.450	3.5	-	-
Machined to	0.800 x 0.460	-	-	-
0.800 x 0.460	0.752 x 0.450	15.3	1000/15	369
0.752 x 0.450	0.700 x 0.430	16.0	1000/15	368
0.700 x 0.430	0.662 x 0.420	14.2	1000/15	369
0.662 x 0.420	0.615 x 0.410	19.8	1000/21	344
0.615 x 0.410	0.587 x 0.395	10.2	1000/17.5	363
0.587 x 0.395	0.550 x 0.380	16.1	1000/15	363
0.550 x 0.380	0.525 x 0.370	12.2	1000/12.5	364
0.525 x 0.370	0.500 x 0.360	13.2	1000/16.5	367
0.500 x 0.360	0.475 x 0.350	14.4	1000/10	360
0.475 x 0.350	0.450 x 0.340	15.7	1000/11	346
0.450 x 0.340	0.425 x 0.325	13.8	1000/12	364
0.425 x 0.325	0.400 x 0.310	14.8	1000/12	375
0.400 x 0.310	0.385 x 0.305	13.6	1000/15	360
0.385 x 0.305	0.364 x 0.290	12.4	1000/15	348
0.364 x 0.290	0.345 x 0.280	16.1	990/12	364
0.345 x 0.280	0.330 x 0.272	14.1	1000/24	357
0.330 x 0.272	0.314 x 0.263	15.7	1000/12	352
0.314 x 0.263	0.295 x 0.250	16.5	1000/12	350
0.295 x 0.250	0.285 x 0.242	7.8	1000/12	358
0.285 x 0.242	0.269 x 0.233	20.2	1000/12	359
0.269 x 0.233	0.250 x 0.218	22.5	1000/12	364
0.250 x 0.218	0.230 x 0.200	8.2		

A P P E N D I X   C

PULSE MAGNETIC WELDING

APPENDIX C

PULSE MAGNETIC WELDING

The feasibility of pulse magnetic welding on ODS alloys was demonstrated on both MA956 and MA957 tubing. The MA956 cladding samples were machined from 0.490 inch bar stock provided by Inco Alloys International. The MA957 cladding samples were from the developmental tubing fabricated by Superior Tube Company. The results from these tests are summarized in Tables C1 and C2.

TABLE C1

RESULTS FROM PULSED MAGNETIC WELDING FEASIBILITY TESTS

MATERIAL (PRIOR HEAT TREATMENT)	SAMPLE NUMBER	KILOVOLTS	He LEAK TEST	AXIAL BOND LENGTH, MILS	CIRCUM. BOND LENGTH, DEGREES	METALLOGRAPHY
MA956 (none)	16307	35.0	----	40 to 70	360	Solid state weld No cracks
MA956 (none)	16308	35.0	----	0 to 50	220	Solid State weld No cracks
MA957 (1000°C)	16586	35.0	----	none	none	----
MA957 (1000°C)	16592	35.0	Leaker	20 to 40	150	----
MA957 (1000°C)	16603	36.0	No leak	20 to 100	360	Solid state weld No cracks
MA957 (900°C)	16614	36.0	No leak	20 to 50	360	Solid state weld No cracks
MA957 (900°C)	16615	36.5	No leak	50 to 100	360	Solid state weld No cracks

TABLE C2

AVERAGE HARDNESS VALUES IN WELDED SAMPLES (DPH)

MATERIAL (PRIOR HEAT TREATMENT)	SAMPLE NUMBER	HT9 END CAP	CLAD APPROX 0.3 INCH FROM WELD REGION	CLAD ADJACENT TO WELD	CLAD/HT9 WELD INTERFACE
MA956 (None)	16308	272	327	358	348*
MA957 (1000°C)	16603	284	407	407	323
MA957 (900°C)	16615	274	429	428	359

* Single hardness value; others are average of two and three values.