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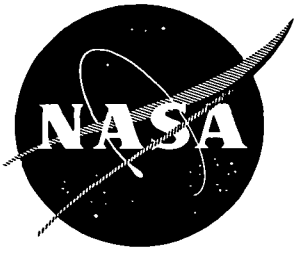

FURTHER DEVELOPMENT AND CHARACTERIZATION OF VM-103, A NASA WROUGHT COBALT-BASE ALLOY

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16. Abstract

The data obtained during this and previous programs indicate that the VM-103 alloy has useful strength at temperatures as high as 2200°F (1204°C), and can be considered as an alternate for other wrought superalloys such as L-605. The addition of 10 percent nickel to the standard composition improves both the hot and cold fabricability, ductility, impact strength, and metallurgical stability, while it only slightly reduces strength properties. Electroslag remelting was effective in significantly increasing the fabricability of vacuum induction method VM-103, both with and without the 10% nickel addition. A specification for wrought VM-103 was developed and is included. Although thermomechanical processing improves lower temperature properties, no improvement occurs at temperatures at or above 2000°F (1093°C).

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1. INTRODUCTION

During 1968 and 1969 in the interest of meeting the demands for higher temperature, higher strength alloys created by advanced propulsion and ordnance programs, Aeronutronic conducted a development program involving NASA's high strength cobalt base superalloy (Co-25W-3Cr-1Ti-.5 Zr-.5C), designated as VM-103. This alloy is one of a series of NASA alloys that shows potential for application to gas turbine engine components, i.e., stator vanes, combustion chamber liners, and high temperature ducting. The alloy also appears competitive with conventional wrought nickel and cobalt base superalloys such as Rene 41, Hastelloy X, Waspaloy, and L-605 for advanced ramjet, scramjet, and rocket engine components. VM-103 appeared particularly promising for short-term, high temperature applications associated with advanced missile guidance systems, i.e., hot gas valves, hydraulic power units, and steering fin actuators, and also for high cyclic rate gun components such as barrels, barrel-liners, or muzzle breaks.

Aeronutronic's program on the alloy consisted of an assessment of the alloy's capability to satisfy design requirements for various missile, propulsion, and gun components. Conventional and high strain rate tensile tests, electron beam welding, preliminary hot and cold working of the alloy, and cold forming and testing of hot gas valve components were accomplished. The results confirmed the apparent applicability of the alloy for the aforementioned high temperature applications.

As an initial step toward advancing the alloy beyond its research status, Aeronutronic then conducted alloy optimization studies for purposes of determining castability and cast properties and to optimize carbon content. Following this, four heats of the alloy were produced utilizing two production oriented melting processes, i.e., vacuum arc remelting (VAR) and electroslag remelting (ESR). The heats were characterized with respect to microstructure and composition, and preliminary forging trials were made which confirmed the adaptability of the alloy to production processes.

Under Contract NAS3-12421, "Development and Metallurgy Study of a NASA Cobalt Base Superalloy," an extensive effort was performed with the objective of further advancing the status of VM-103 from that of research toward production. Hot and cold working parameters, and solution and aging heat treatments, were established; room and elevated temperature conventional and high strain rate tensile properties were developed, and a

microstructure and phase identification study was performed. Comparative fabricability and properties of two melting processes showed that ESR appears more favorable than the VAR process for this alloy.

A flow chart showing VM-103 development from the early NASA 1700 g heats through Contract NAS3-12421 is shown in Figure 1. All VM-103 R&D efforts were very encouraging and indicated that VM-103 had good potential for an ultimate production high temperature superalloy. However, during the earlier work, various areas requiring further development were identified[3]. There were indications that further work to optimize chemical composition and processing parameters would be useful in efforts to further improve fabricability and mechanical properties. Effects of selected alloying additions and of alloy impurities remained unknown. In addition, earlier data indicated that VM-103 might be responsive to thermomechanical processing treatments which was considered worthy of investigation for enhancing mechanical properties.

The objective of the program covered in this report was to further evaluate the effects of the chemistry variation and processing variables on the mechanical and physical properties of NASA alloy VM-103. A secondary objective was to develop sufficient data so that a procurement specification for VM-103 could be prepared.

The program was divided into four tasks, briefly described below:

Task I - Thermomechanical Processing

The goal of this task was to develop thermomechanical processing parameters to enhance the mechanical properties of VM-103, particularly in the 1800-2200°F (982-1204°C) range.

Task II - Alloy Improvement

This task was designed to investigate the effects of melting technique, impurities, and alloy additions on the fabricability and properties of VM-103. Further improvement of electroslag remelted (ESR) material properties were also investigated.

Task III - Property Evaluation

This task was to determine additional design property data on VM-103 such as impact strength, hot hardness, coefficient of thermal expansion, density, and creep rupture.

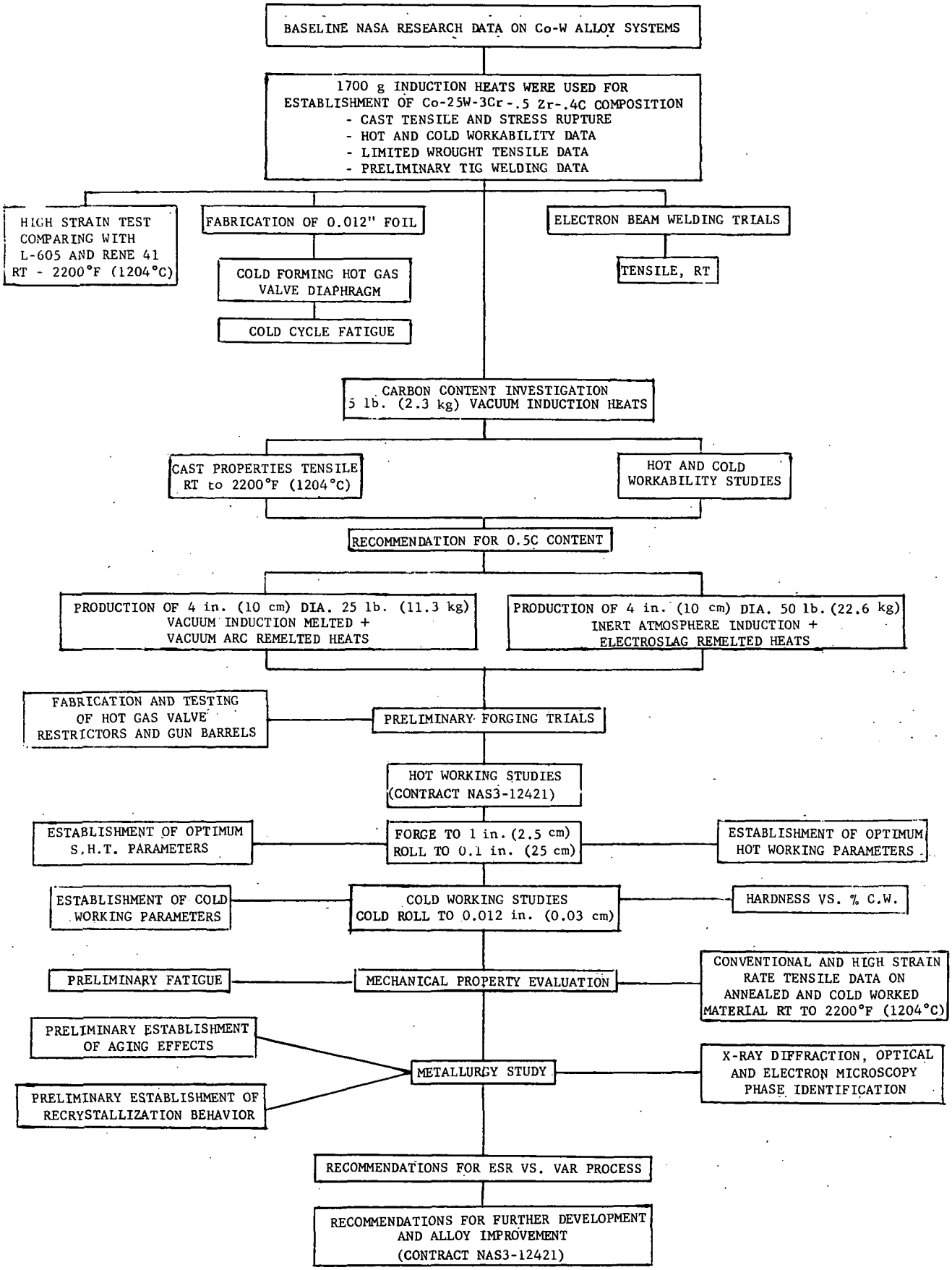


FIGURE 1. VM-103 ALLOY DEVELOPMENT

Task IV - VM-103 Procurement Specification

The objective of this task was to prepare procurement specifications for wrought VM-103 based on existing information and additional data developed by Tasks I, II and III of this program.

2. PROCEDURE

Material

The early work on VM-103 was conducted on small 3-4 pound (≤2 kg) vacuum or inert atmosphere, single induction melted laboratory type heats. The melting practices were upgraded by Contract NAS3-12421 to more conventional superalloy production, i.e., duplex melting practices consisting of vacuum induction melting (VIM) plus vacuum arc remelting (VAR) and vacuum induction melting (VIM) plus electroslag remelting (ESR). ESR is a relatively new process that is similar in principle to the VAR process. Both processes start with a VIM cast electrode, the VAR material is arc remelted in a vacuum to reduce microsegregation inherent in VIM material. To reduce volatile type impurities by allowing the molten material to outgas: the ESR material is also arc remelted from VIM material; however, the melting occurs in a specially prepared molten slag blanket which reacts with the volatile materials and some of the nonvolatile impurities. The ESR melting practice has been shown to generally improve such properties as ductility, fabricability, fatigue strength and fracture toughness of various steels and nickel base superalloys.[1,2].

The Task I thermomechanical processing phase of the current program was conducted on residual material (Heats PF-11 and PF-288) from Contract NAS3-12421[3]. Heats PF-11 and PF-288 were 50 pound (23 kg) ESR material supplied by ESCO Corporation, Portland, Oregon. Chemistry analyses of the two heats are presented in Table I; all metallic elements reported were determined by X-ray spectroscopy, the carbon was determined by gas analysis. Although these heats did not meet the VM-103 target analyses for tungsten and zirconium the material was considered acceptable for the thermomechanical processing portion of the program.

The Task II Alloy Improvement phase of the program was designed to evaluate the effect of melting processes and of selective alloy additions on the fabricability and mechanical properties of the basic VM-103 alloy. Eight 5-10 pound (2.3 - 4.5 kg) heats listed in Table II were melted during the Task II phase of the program. Two additional heats of the B3 composition were melted by the VIM process and cast directly into round tensile specimens for creep rupture evaluation during Task III. Table III shows the chemical analyses of all the heats used in the program.

TABLE I

CHEMICAL ANALYSES OF TASK I MATERIAL
(Weight Percent)

Elements	Target Analysis	Heat Number	
		PF-11	PF-288
Tungsten	25	24.13	28.15
Chromium	3	2.51	3.00
Titanium	1	0.95	1.06
Zirconium	0.5	0.25	0.24
Carbon	0.5	0.50	0.45
Iron	0.1 Max.	1.08	0.16
Cobalt	Balance	Balance	Balance

TABLE II

MELTING PRACTICE AND CHEMICAL COMPOSITION VARIABLES INVESTIGATED

Heat Number	Melting Practice	Target Composition[c]
A1	VIM[a]	Standard VM-103
A2	VIM	Standard VM-103 + 10% Ni
A3	VIM	Standard VM-103 + 10% Ni + 5% Fe
B1	VIM	Standard VM-103 + 0.25-0.50% Si + 0.25-0.50% Mn
B2	VIM	Standard VM-103 + 10% Ni + 0.25-0.50% Si + 0.25-0.50% Mn
B3	VIM + ESR[b]	Standard VM-103 + 10% Ni
B4	VIM + ESR	Standard VM-103

[a] VIM = Vacuum Induction Melt

[b] ESR = Electroslag Remelt

[c] Standard VM-103 Composition 25% W, 3% Cr, 1% Ti, 0.5% Zr, 0.5% C, 0.1 max Fe and balance Co.

TABLE III

CHEMICAL ANALYSIS OF STANDARD AND MODIFIED VM-103 HEATS

(WEIGHT PERCENT)

Elements	Standard VM-103 Nominal Composition	Heat Identification									
		A1 VIM[a]	A2 VIM	A3 VIM	B1 VIM	B2 VIM	B2-2 VIM	B3 VIM-ESR[b]	B3-C1 VIM[a]	B3-C2 VIM	B4 VIM-ESR
Tungsten	25	25.0	24.70	25.12	24.50	24.95	24.90	24.80	24.80	24.76	24.80
Chromium	3	3.16	2.98	3.18	3.02	3.10	3.10	3.06	3.06	3.07	3.16
Titanium	1	1.07	1.10	1.10	1.14	0.85	1.05	1.05	1.02	0.99	1.10
Zirconium	0.5	0.52	0.42	0.52	0.50	0.50	0.50	0.45	0.49	0.49	0.45
Carbon	0.5	0.52	0.55	0.52	0.47	0.46	0.43	0.50	0.48	0.38	0.49
Iron	0.1 max	0.12	0.12	4.12				0.12			0.12
Nickel		0.13	10.30	10.70		10.05	11.50	10.50	10.50	10.40	0.17
Manganese		0.04	0.04		0.72	0.28	0.50	0.01			0.04
Silicon		0.10	0.10		0.28	0.50	0.45	0.15			0.10
Hydrogen		0.0001	0.0001	0.0001			0.0004		0.00026	0.0002	0.0001
Oxygen		0.002	0.002	0.0015		0.0002	0.0001		0.0026	nil	0.0005
Nitrogen		0.0055	0.0055	0.0047		0.0033	0.0088	0.019	0.0030	0.018	0.0020
Cobalt	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal

Heat Identification

A1: Standard VM-103
A2: Standard VM-103 + 10% Ni
A3: Standard VM-103 + 10% Ni + 5% Fe
B1: Standard VM-103 + 0.25-0.50% Si + 0.25-0.50% Mn
B2: Standard VM-103 + 10% Ni + 0.25-0.50% Si + 0.25-0.50% Mn
B3: Standard VM-103 + 10% Ni
B4: Standard VM-103

[a] VIM = Vacuum Induction Melt.

[b] VIM-ESR = Vacuum Induction Melt + Electroslag Remelt.

Ingot Reduction

Forging

The cast ingots were conditioned for forging by grit blasting to remove any surface impurities and allow assessment of the ingot quality. Surface imperfections were removed by hand grinding of local defects or rough turning to remove more severe conditions. The pipe or suckback on the top of the ingot was removed by sectioning and hand grinding as required.

The forging was conducted at West Coast Forge, Compton, California, with a 3500 pound (15,900 N) hammer forge. The 4 inch (10 cm) diameter ingots were forged to 1 x 1 inch (2.5 x 2.5 cm) bar using the parameters developed on Contract NAS3-12421 and listed below:

(1) Soak at 2175°F (1190°C) for 1/2 hour.

(2) Forge in radial direction to 3 x 3 in. (7.6 x 7.6 cm) square using reductions of approximately 8-10 percent.

(3) Return to furnace after each reduction; soak at temperature for 15 minutes.

(4) Forge to 1 x 1 in. (2.5 x 2.5 cm) square using 15-20 percent reductions.

(5) Return to furnace after each reduction; soak at temperature for 10 minutes.

(6) After last pass, soak at 2200°F (1204°C) for 10 minutes and water quench.

(7) Inspect after each reduction; grind or crop any surface defects as required.

Rolling

The 1 x 1 inch (2.5 x 2.5 cm) forged bar was further reduced to 0.10 inch. (0.25 cm) at Aeronutronic by the optimum hot rolling techniques developed on Contract NAS3-12421.[3] The bars were preheated at 2175°F (1190°C) for 30 minutes and rolled on a 2 high - 4 high rolling mill. The initial passes were limited to 12-15 percent with subsequent reductions of 15-35 percent. The material was reheated between passes at 2175°F (1190°C) for 3 to 10 minutes, depending on the material thickness and soaked at 2200°F (1204°C) for 10 minutes and water quenched after the last pass. Test samples were given additional reductions by combinations of hot and cold rolling to investigate the effect of thermomechanical processing on the VM-103 alloy. Cold reductions of up to 40 percent were evaluated.

Heat Treatment

Solution Heat Treatment

The optimum solution heat treatments with respect to minimum hardness, minimum grain growth and minimum matrix or grain boundary carbide precipitation was established during Contract NAS3-12421.[3] The optimum solution heat treatment was 2200°F (1204°C) for 30 minutes followed by a water quench. The samples were processed in a circulating air atmosphere furnace and subsequently grit blasted to remove the oxide scale.

Aging

The VM-103 alloy was designed to be a solid solution strengthened alloy; however, preliminary NASA data and data generated on Contract NAS3-12421[3] indicated a potential aging phenomenon. Aging studies were used in conjunction with prior annealing or cold reduction to investigate thermo-mechanical processing as a useful strengthening mechanism for elevated temperature 2000-2200°F (1093-1204°C) service. Samples were encapsulated in quartz tubes, evacuated to 10^{-5} torr and sealed to prevent oxidation during aging at the time-temperature combinations shown by Figure 2. Hardness measurements, metallography and mechanical testing of selected samples were utilized to evaluate the aging effects.

Mechanical Testing

Hardness Testing

Room temperature hardness tests were conducted with a standard Rockwell hardness tester. Samples were evaluated throughout the program as an indication of the effects of processing on the VM-103 material.

Hot hardness measurements were taken at 1000, 1200, 1400 and 1600°F (538, 649, 760 and 871°C) with a standard Wilson Rockwell hot hardness tester on samples from two VM-103 heats (B3 and B4) in the following conditions:

(1) Solution heat treated.

(2) Solution heat treated plus aged.

(3) Solution heat treated plus 25 percent reduction at 75°F (24°C).

(4) Solution heat treated plus 25 percent reduction at 75°F (24°C) plus aged.

Solution heat treated = 2200°F (1204°C) for 1/2 hour, water quench

Aged = 1300°F (704°C) for 10 hours.

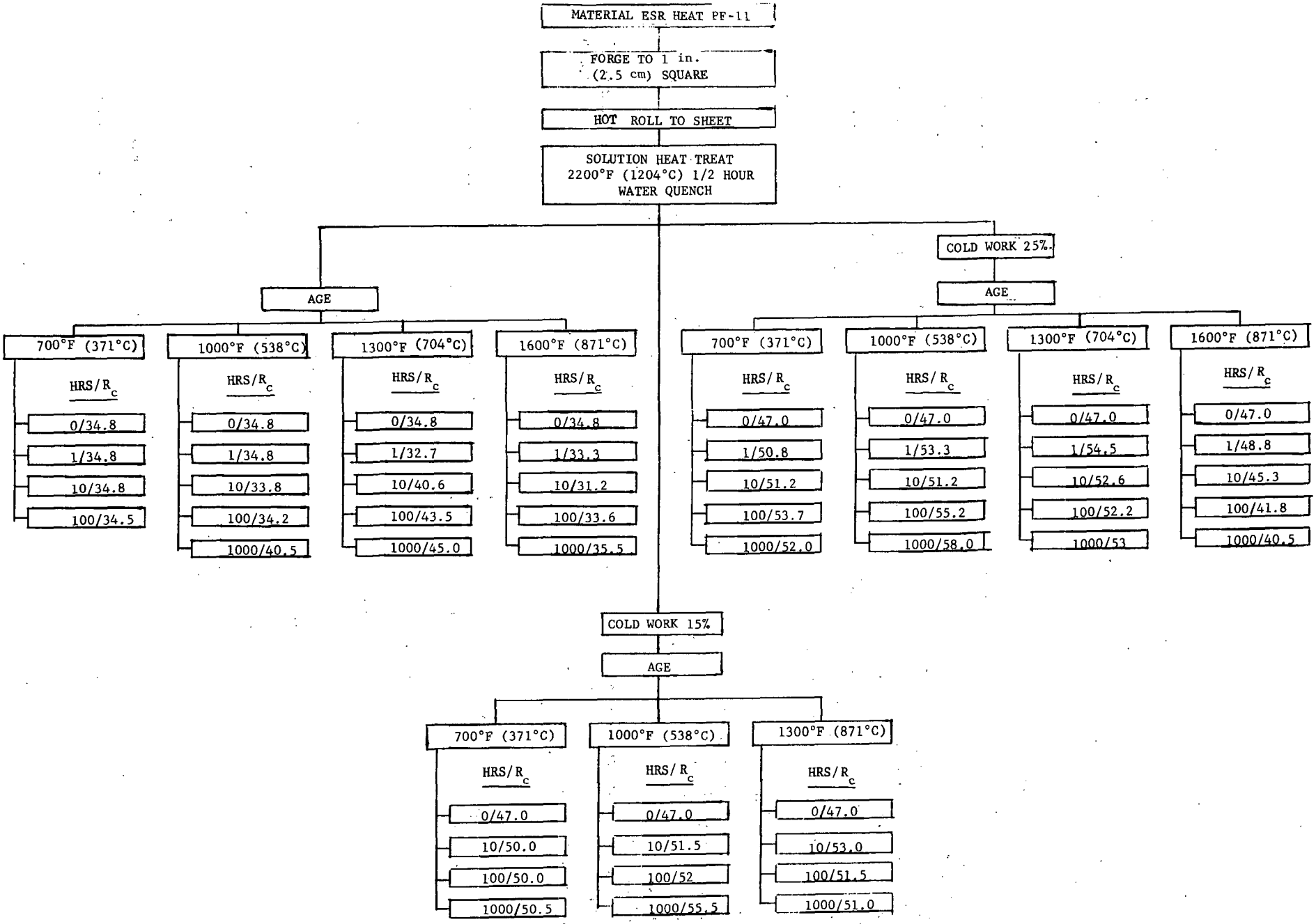


FIGURE 2. AGING PARAMETERS AND RESULTING HARDNESS

Samples approximately 1/2 x 2 x 0. 100 inch (1. 3 x 5. 1 x 0. 25 cm) with an 0. 125 inch (0. 317 cm) diameter hole drilled approximately half way through the specimen were used in the evaluation. The specimen temperature was measured with a thermocouple inserted in the hole. Each sample was heated to 1000°F (538°C) held for 15 minutes and evaluated using a standard Wilson hot hardness tester , then raised to the next higher temperature.

Tensile Testing

The room and elevated tensile properties of annealed and thermally processed material were determined on a 10, 000 pound (44, 500 N) capacity Instron testing machine equipped with a 2200°F (1204°C) resistance furnace. The specimens were brought from ambient to test temperature in about 30 minutes, soaked at temperature for an additional 15 minutes and then tested at a strain rate of 0. 005/minute to 0. 4 percent offset yield followed by 0. 05/minute to failure. An extensometer was used for measuring strain until about 1 percent elongation. The specimens were machined to the configuration shown in Figure 3.

High Strain Rate Tensile Testing

Rectangular sheet specimens, 4 x 0. 25 inch (10 x 0. 6 cm) were fabricated from 0. 040 inch (0. 1 cm) thick sheet material with various amounts of thermomechanical processing. The specimens were tested on a "Gleeble" machine at a strain rate of 5/minute at temperatures of 75, 1200, 1600, 1800, 2000 and 2200°F (23, 649, 871, 982, 1093 and 1204°C). The samples were electrically self-resistance heated at a rate of approximately 500°F (260°C)/second, and held at temperature either for 5 or 30 seconds prior to application of the load.

Impact

Standard V notch Charpy impact specimens were machined from material from heats B3 and B4 in the following conditions:

(1) Solution heat treated.

(2) Solution heat treated plus aged.

(3) Solution heat treated plus 25 percent reduction at 75°F (24°C).

(4) Solution heat treated plus 25 percent reduction at 75°F (24°C) plus aged.

Solution heat treated = 2200°F (1204°C) for 1/2 hour, water quench

Aged = 1300°F (704°C) for 10 hours.

Duplicate specimens were evaluated at room temperature and -65°F (-54°C).

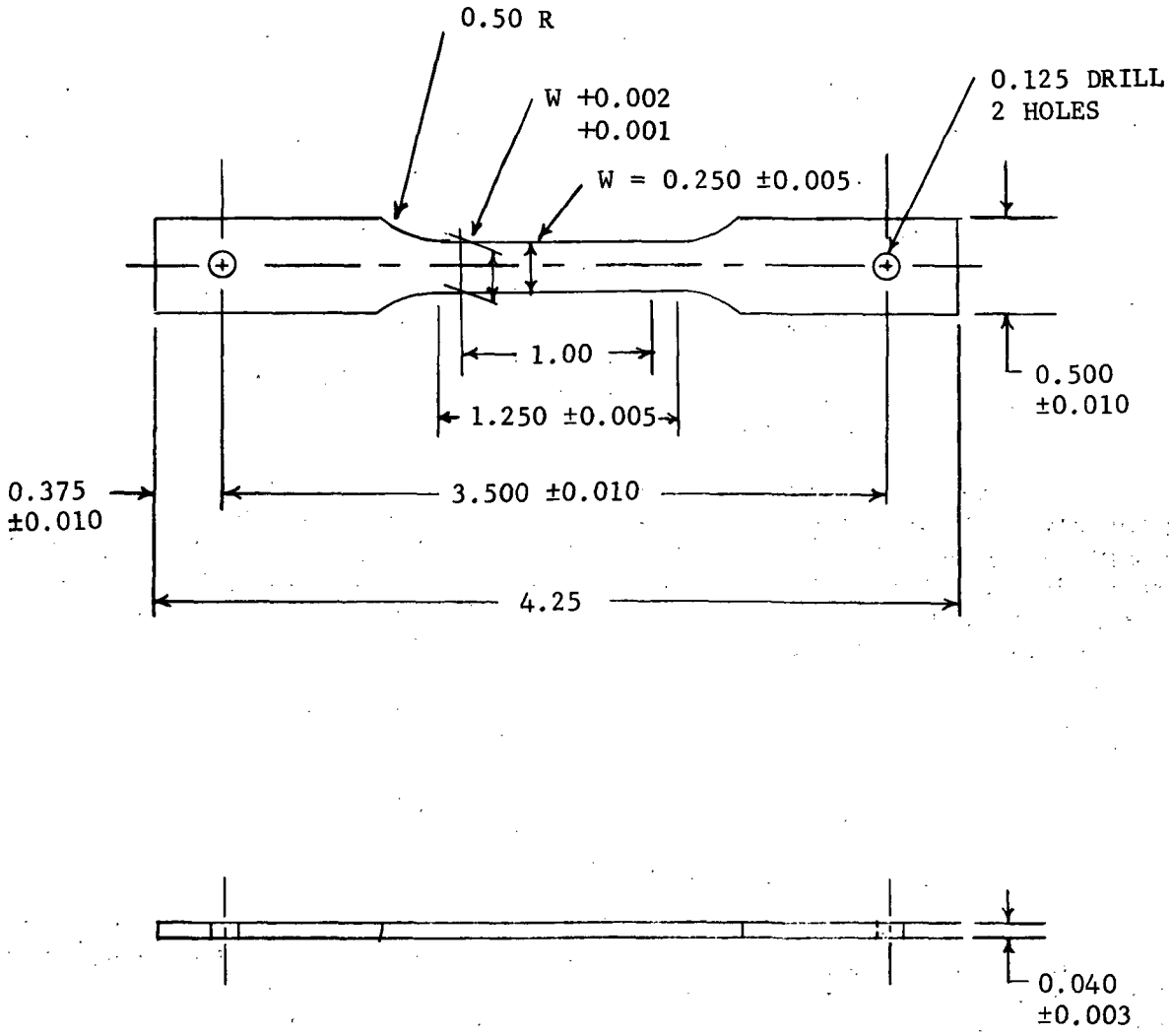


FIGURE 3. VM-103 SHEET TENSILE SPECIMEN
(ALL DIMENSIONS IN INCHES)

Metallurgical Analysis

Metallography

Selected samples were prepared for metallographic observation using the following method:

(1) Successive grinding on 180, 240, 360 and 600 grit silicon carbide.

(2) Polish on 6 micron diamond followed by 1 micron diamond.

(3) Final polish on 0.05 micron alumina.

(4) Etch by swabbing for 4 to 8 seconds with hydrochloric acid saturated with ferric chloride.

(5) Ultrasonically clean for 2 to 3 minutes in distilled water.

A Leitz MM-5 metallograph was used for optical microscopy and photographed using bright field illumination. Observations were made at magnifications from 100 to 1000X. Grain size measurements were obtained using the ASTM-E-112 linear intercept method. The reported grain sizes refer to the calculated "diameter" of an average grain with a mean standard deviation of $\pm$ 10 percent.

3. RESULTS AND DISCUSSION

Task I - Thermomechanical Processing

Background

One of the state-of-the-art methods for improving the mechanical properties of metallic systems is through thermomechanical processing. The majority of thermomechanical processing studies have been related to steels,[4, 5] although some work has been conducted on aluminum[4-8] and superalloys[9-11]. Basically, thermomechanical processing involves combination of thermal and deformation treatments that result in a rearrangement of the defect and minor phase structure with corresponding changes in the mechanical properties. Strengthening effects result from an increased and more uniform dislocation density which is achieved through thermomechanical processing by different mechanisms depending on the alloy system and prior treatment[4]. In steels, thermomechanical processing increases dislocation density primarily through working; precipitates increase this effect but to a minor extent.

In other systems such as the aluminum alloys an increased number of nucleation sites for the precipitation hardening reaction are generated in addition to the more uniform and increased matrix strengthening[7]. More uniform matrix precipitates can also be achieved in cobalt-base alloys such as L-605 by aging deformed material[10]. By selection of proper thermomechanical processing parameters for deformation and aging treatments it is possible to obtain an alloy with a uniform secondary phase distribution. The process may result in increased alloy strength by hindering dislocation motion through interaction with other dislocations or phases. However, the ductility is not necessarily reduced to the same degree as for conventionally processed materials of the same strength. This can be explained by the fact that a more uniform deformation occurs by the movement of a greater number of dislocations over a small area per dislocation.

Data generated on Contract NAS3-12421[3] indicated that VM-103 may be responsive to thermomechanical treatments as a means for achieving improved mechanical properties. In particular the data showed:

(1) Rapid work hardening characteristics as shown in Figure 4.

(2) Response of cold worked and solution heat treated material in aging treatments as shown in Figure 5.

(3) Beneficial effects of aging solution heat treated material resulting in an increase in 2200°F (1204°C) yield strength from 4.1 to 10.1 ksi (28.4 to 69.7 N/mm^2) or 140 percent.

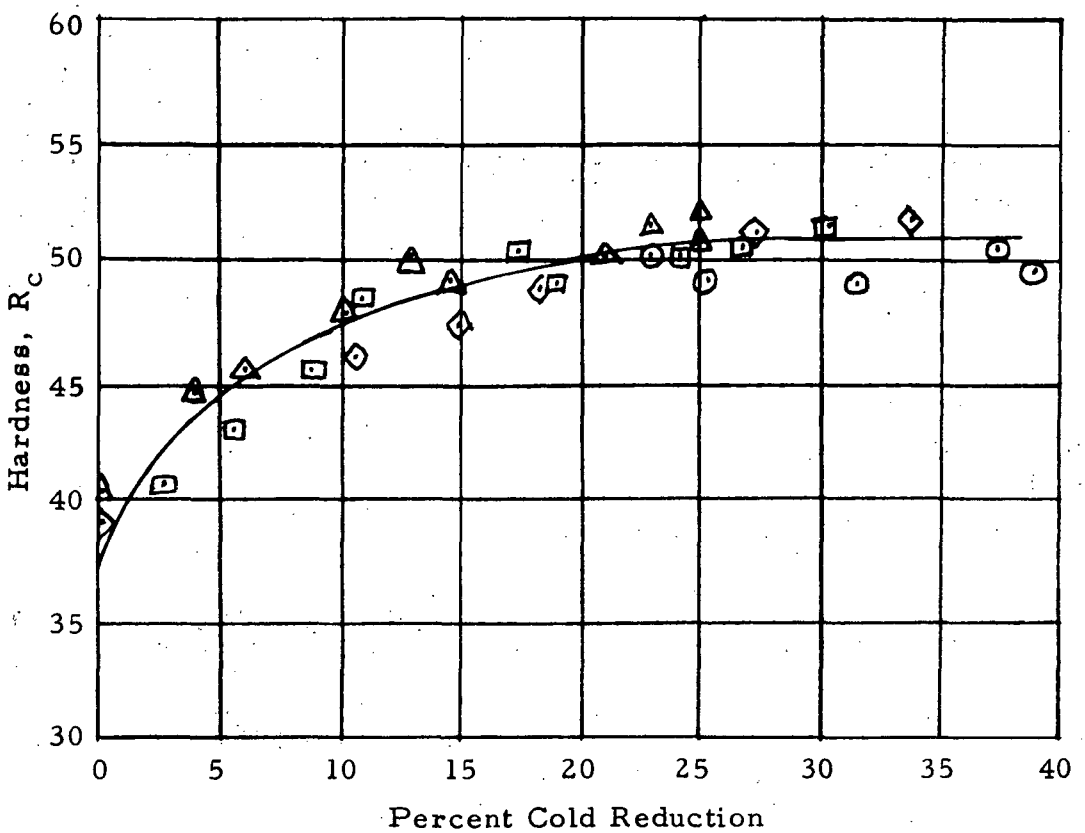
(4) A possible rapid aging effect evidenced by varying the holding times on elevated temperature high-strain rate tests, Table IV.

Scope

Task I was designed to develop thermomechanical processing parameters to enhancing the mechanical properties of VM-103, in the 1800 to 2200°F (982 to 1204°C) range.

Material

As indicated above, residual material from Contract NAS3-12421[3] was utilized for the Task I thermomechanical processing evaluation. Two 50-pound (23 kg) electroslag remelted heats (PF-11 and PF-288) were supplied by ESCO Corporation, Portland, Oregon. The chemical analysis of the two heats are presented in Table I. The cast ingots were forged from a 4 inch (10 cm) diameter to a 1 x 1 inch (2.5 x 2.5 cm) square bar and solution heat treated at 2200°F (1204°C) for 1/2 hour and water quenched without cooling from the forging operation. The material was subsequently hot rolled to various thicknesses and resolution heat treated to provide starting material for the thermomechanical processing study.



Symbol	Melting Process	Heat Number
⊡	VAR	20-1
◇	VAR	20-5
⊙	ESR	PF-11
△	ESR	PF-13

VAR: Vacuum Arc Remelt
ESR: Electroslag Remelt

FIGURE 4. HARDNESS VS. PERCENT COLD REDUCTION OF VM-103[3]

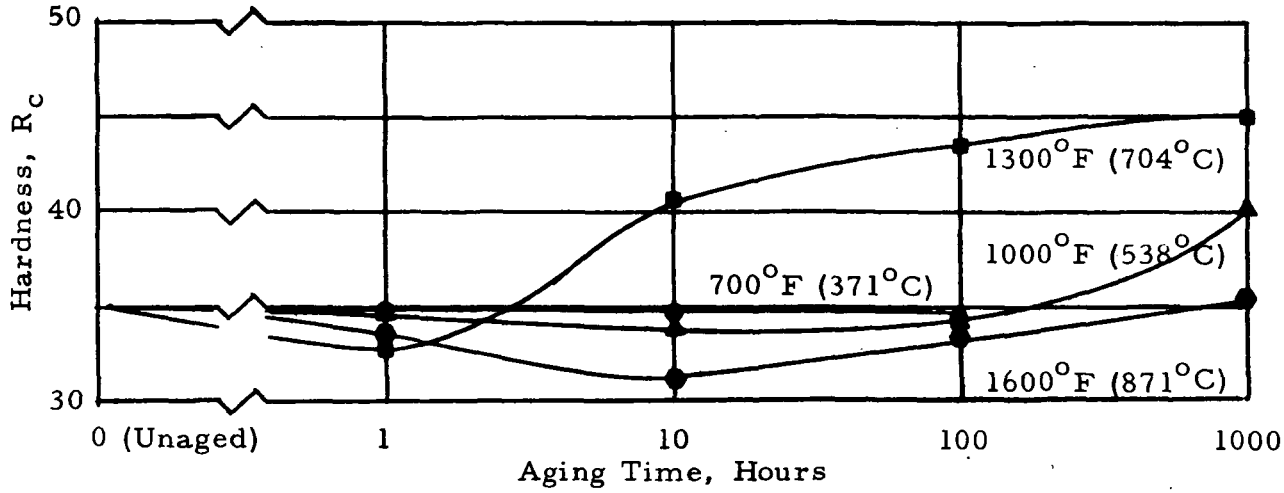


FIGURE 5A. EFFECT OF AGING TIME AT INDICATED TEMPERATURE ON THE HARDNESS OF SOLUTION HEAT TREATED VM-103

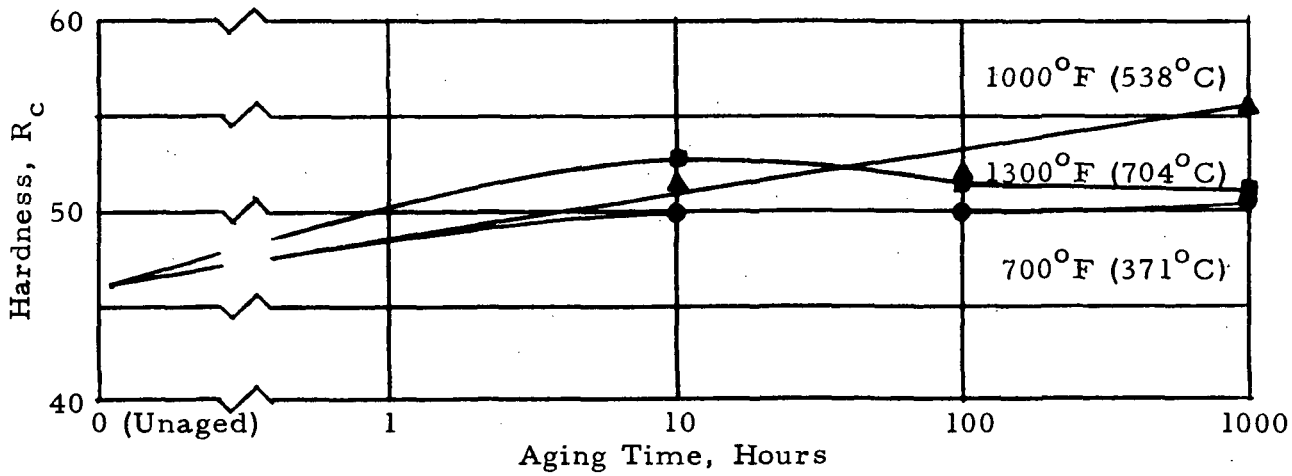


FIGURE 5B. EFFECT OF AGING TIME AT INDICATED TEMPERATURE ON THE HARDNESS OF 15% REDUCTION 75°F (24°C) VM-103

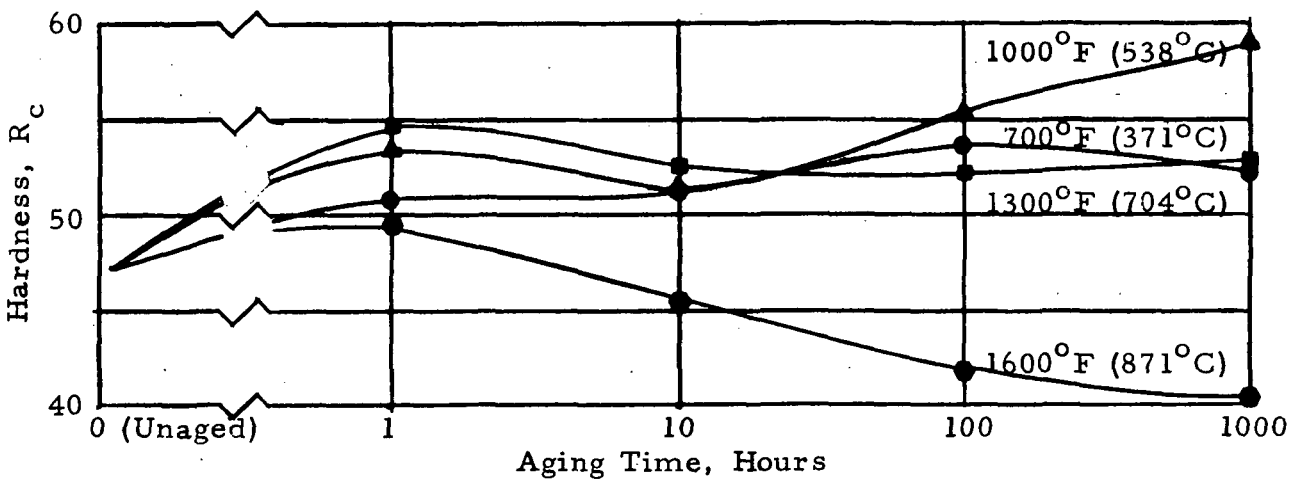


FIGURE 5C. EFFECT OF AGING TIME AT INDICATED TEMPERATURE ON THE HARDNESS OF 25% REDUCTION (75°F (24°C) VM-103

TABLE IV

HIGH STRAIN RATE* TENSILE PROPERTIES OF ESR HEAT PF-11[3]

**Condition	Temperature °F	Temperature °C	Time at Temperature, Sec.	0.2% Offset Yield Strength ksi	0.2% Offset Yield Strength N/mm²	Ultimate Tensile Strength ksi	Ultimate Tensile Strength N/mm²	Elongation in 0.8 In. (2.0 cm) %	Reduction of Area %
15% RED.	75	24	--	190.0	1,310	211.7	1,460	0.3	--
25% RED.	75	24	--	202.3	1,395	208.4	1,437	0.3	--
25% RED.	75	24	--	194.4	1,340	213.0	1,469	0.3	--
SHT	75	24	--	158.0	1,089	175.0	1,207	0.4	--
15% RED.	1800	982	5.0	--	--	50.6	349	15.0	63
15% RED.	1800	982	25.5	48.5	334	55.7	384	16.3	62
25% RED.	1800	982	4.8	38.5	265	44.1	304	18.8	53
25% RED.	1800	982	15.1	42.9	296	51.8	357	17.5	55
SHT	1800	982	5.0	40.3	279	49.2	339	20.0	47
SHT	1800	982	25.6	40.2	277	50.1	345	22.5	51
15% RED.	2000	1093	5.1	24.9	172	28.1	194	25.0	53
15% RED.	2000	1093	25.2	27.3	188	29.0	200	23.8	52
25% RED.	2000	1093	5.1	25.0	172	27.9	192	27.5	50
25% RED.	2000	1093	25.3	27.4	189	28.3	195	26.0	60
SHT	2000	1093	25.2	30.5	210	31.5	217	28.5	72
15% RED.	2200	1204	5.0	18.5	128	18.7	129	23.7	54
15% RED.	2200	1204	25.8	17.8	123	17.9	123	22.5	51
SHT	2200	1204	5.0	18.3	126	18.5	128	22.5	53
SHT	2200	1204	25.7	18.4	127	18.8	130	30.0	82

*Strain Rate: 5/min.

**RED: Reduction at 75°F (24°C)
SHT: Solution heat treat, 2200°F (1204°C), 1/2 hour water quench

Thermomechanical Processing Studies

Early NASA data indicated an aging phenomenon in VM-103 particularly in the 1600°F (871°C) range, resulting from the precipitation of a Co_3W phase. One goal of the NAS3-12421[3] program was to achieve a better understanding of this effect and to determine if aging would be useful as a strengthening mechanism. Specimens representing annealed and 25 percent cold worked sheet were encapsulated in evacuated quartz tubes and aged for one, ten and 100 hours at temperatures of 700, 1000, 1300 and 1600°F (371, 538, 704 and 871°C). The current program expanded the previous work to include 15 percent cold worked material and lengthened the exposure periods to 1000 hours. The complete test matrix and results obtained from both programs on heat PF-11 are shown in Figure 2, the results are also presented graphically in Figure 5A, B and C.

Based on the hardness results, the aging studies showed that the alloy is significantly responsive to age hardening at 1300°F (704°C) both in the solution treated and cold worked conditions. The 25 percent cold worked material exhibited a decrease in hardness when aged for extended periods at 1600°F (871°C). Material with 15 percent cold worked showed a similar behavior when aged at 700, 1000 and 1300°F (371, 538 and 704°C), the hardness was about two Rockwell "C" points below that obtained for the 25 percent cold worked material.

Samples of VM-103 sheet from heat PF-288 were subjected to approximately 40 variations in thermomechanical processing combinations of cold, warm and hot rolling, aging at various times and temperatures. Figure 6 shows a flow sheet for the thermomechanical process and the resulting room temperature hardness values are shown by Table V. Some of the processing parameters increased the hardness from approximately R_c 35 to R_c 57.5 and above. The nine processes, (3, 7, 13, 21, 29, 37, 41, 42 and 43, Table VI) resulting in the maximum room temperature hardness were selected for tensile testing and compared to solution treated material.

Tensile specimens of the configuration shown by Figure 3 were evaluated at 2000 and 2200°F (1093 and 1204°C). The test parameters included a soak period of 5 minutes and a strain rate of 0.005/minute to yield followed by 0.05/minute to failure. The results shown by Table VI did not reveal any significant improvements under these test conditions indicating that any beneficial effects of aging or thermomechanical processing were annealed away rather quickly at 2000 and 2200°F (1093 and 1204°C) and the resulting strengths were not significantly different from the solution treated material. Effects of aging or thermomechanical processing for very short times and under high strain rate conditions at 2000 and 2200°F (1093 and 1204°C) were also determined. The samples previously processed for evaluation of the thermomechanical processes were subjected to 5 and 25 second soak times in a salt bath at 2000 and 2200°F (1093 and 1204°C) followed by a water quench. The resulting room temperature hardness values are presented in Table V. Five processes (4, 24, 32, 42 and 45) were selected for additional testing under high strain-rate

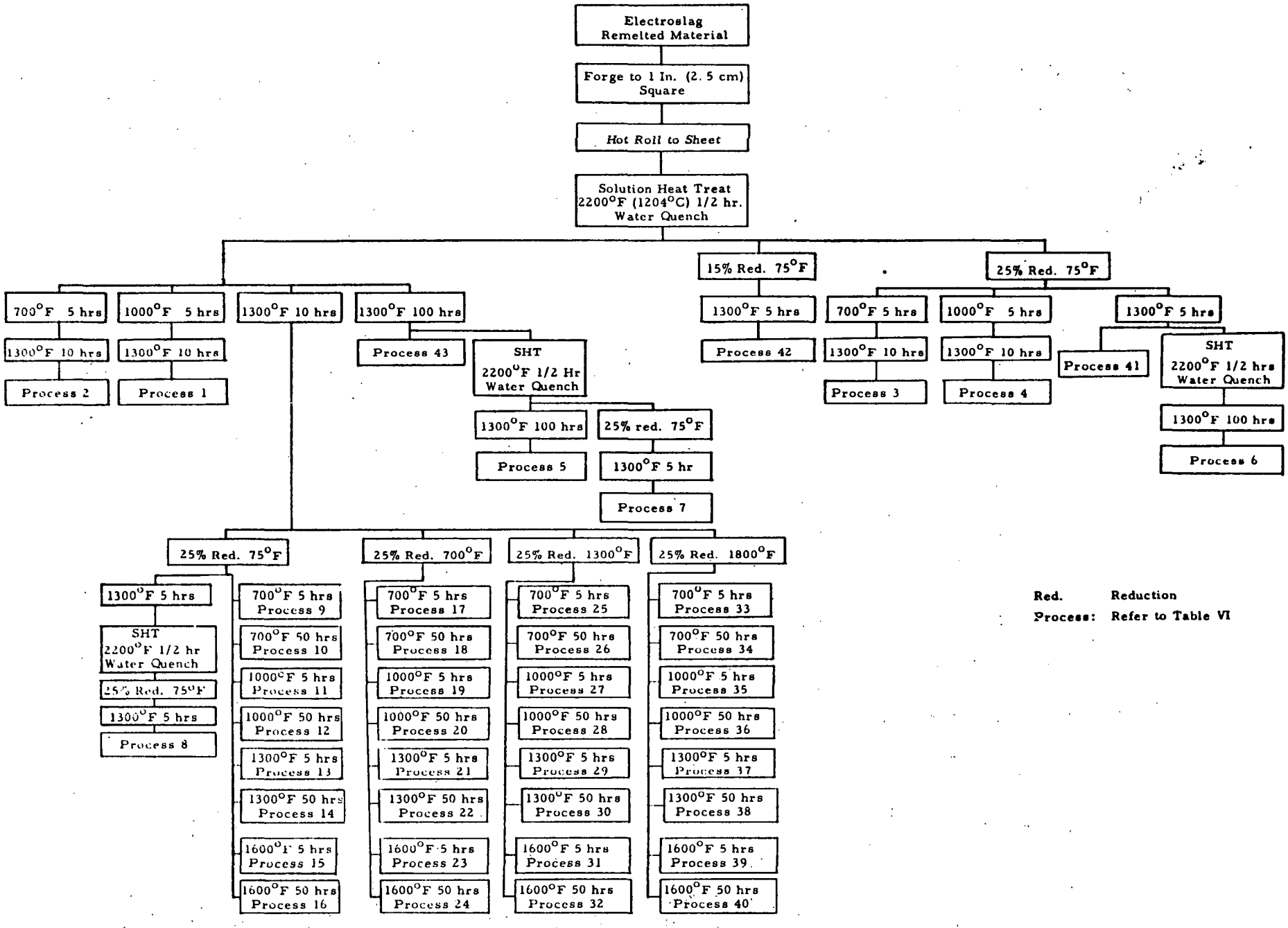


FIGURE 6. THERMOMECHANICAL PROCESSING VARIABLES

TABLE V

HARDNESS OF VM-103 AFTER THERMOMECHANICAL PROCESSING

Proc. No.	Thermomechanical Processing Sequence	Room Temp. As Processed Rc	Annealing Temperature			
			2000°F (1093°C)		2200°F (1204°C)	
			4 sec Rc	25 sec Rc	5 sec Rc	25 sec Rc
1	SHT + 1000°F (538°C), 5 hr + 1300°F (704°C), 10 hr	43	44	37	41.5	36.5
2	SHT + 700°F (371°C), 5 hr + 1300°F (704°C), 10 hr	43.5	45	38	44.5	37
3	SHT + 25% Red., RT + 700°F (371°C), 5 hr + 1300°F (704°C), 10 hr	57.5	57.5	57	57	40
4	SHT + 25% Red., RT + 1000°F (538°C), 5 hr + 1300°F (704°C), 10 hr	57.5	58	57.5	58	40.5
5	SHT + 1300°F (704°C), 100 hr + SHT + 1300°F (704°C, 100 hr	48	49.5	49	49	36.5
6	SHT + 25% Red., RT + 1300°F (704°C), 5 hr + SHT + 1300°F (704°C), 100 hr	47.5	48.5	48	47.5	36.5
7	SHT + 1300°F (704°C),100 hr + SHT + 25% Red., RT + 1300°F (704°C), 5 hr	59	58	57.5	57.5	37
8	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1300°F (704°C), 5 hr + SHT + 25% Red., RT + 1300°F (704°C), 5 hr	56	-	-	-	-
9	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 700°F (371°C), 5 hr	54	54	53.5	53	37.5
10	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 700°F (371°C), 50 hr	53.5	54	47	49.5	37
11	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1000°F (538°C), 5 hr	54.5	55	49.5	48.5	37.5
12	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1000°F (538°C), 50 hr	55	55	52	49	38
13	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1300°F (704°C), 5 hr	57	57.5	54	51	38.5
14	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1300°F (704°C), 50 hr	57.5	58	55	54.5	38
15	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1600°F (871°C), 5 hr	51	52.5	52.5	52.5	37.5
16	SHT + 1300°F (704°C), 10 hr + 25% Red., RT + 1600°F (871°C), 50 hr	48	49	49	49	39.5
17	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 700°F (371°C), 5 hr	55.5	55	52.5	42	37
18	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 700°F (371°C), 50 hr	54	54.5	50.5	43	37
19	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1000°F (538°C), 5 hr	55	55	48.5	47	36.5
20	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1000°F (538°C), 50 hr	55.5	55.5	45.5	44.5	37
21	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1300°F (704°C), 5 hr	58.5	57.5	46	53	39
22	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1300°F (704°C), 50 hr	59	58.5	55	57.5	38.5
23	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1600°F (871°C), 5 hr	52	52.5	52.5	51.5	38.5
24	SHT + 1300°F (704°C), 10 hr + 25% Red., 700°F (371°C) + 1600°F (871°C), 50 hr	49	50	50	48.5	41.5
25	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 700°F (371°C), 5 hr	56	55.5	48	50.5	37
26	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 700°F (371°C), 50 hr	55.5	54	47	50	37
27	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1000°F (538°C), 5 hr	56.5	54.5	47	50.5	37.5
28	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1000°F (538°C), 50 hr	57	55	48	55	39
29	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1300°F (704°C), 5 hr	59	57	51	54	39
30	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1300°F (704°C), 50 hr	59.5	58.5	56	57.5	39.5
31	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1600°F (871°C), 5 hr	53.5	53	53.5	53	40
32	SHT + 1300°F (704°C), 10 hr + 25% Red., 1300°F (704°C) + 1600°F (871°C), 50 hr	51	50	50.5	51	41.5
33	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 700°F (371°C), 5 hr	49.5	49	48	49.5	39
34	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 700°F (371°C), 50 hr	48.5	49	47	48	37
35	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1000°F (538°C), 5 hr	50	48.5	47.5	48	37.5
36	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1000°F (538°C), 50 hr	50	50	47	48.5	37.5
37	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1300°F (704°C), 5 hr	55.5	55.5	50	54.5	37.5
38	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1300°F (704°C), 50 hr	55	56.5	51	55.5	37
39	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1600°F (871°C), 5 hr	52.5	52	52	51	38.5
40	SHT + 1300°F (704°C), 10 hr + 25% Red., 1800°F (982°C) + 1600°F (871°C), 50 hr	50	50.5	50	50.5	41
41	SHT + 25% Red., RT + 1300°F (704°C), 5 hr	57.5	57	55.5	55.5	38
42	SHT + 15% Red., RT + 1300°F (704°C), 5 hr	55	56	54.5	54.5	39.5
43	SHT + 1300°F (704°C), 100 hr	54.5	57.5	49.5	56	39

SHT = Solution heat treat = 2200°F (1204°C), 1/2 hr water quench.
Red = Reduction by rolling expressed in percent (%) of original thickness.

TABLE VI

TENSILE DATA FOR THERMOMECHANICALLY PROCESSED VM-103

(Average of Duplicate Results)

Process Number**	0.2% Offset Yield Strength				Ultimate Tensile Strength				Elongation	
	2000°F (1093°C)		2200°F (1204°C)		2000°F (1093°C)		2200°F (1204°C)		2000°F (1093°C)	2200°F (1204°C)
	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	% in 1 in. (2.5 cm)	% in 1 in. (2.5 cm)
SHT	19.8	137	6.0	41	22.0	151	9.6	66	10	11
3	6.2*	43	4.8	33	14.7*	101	10.3	71	16*	19
7	6.7	46	5.3	37	16.0	110	11.2	77	18*	11
13	9.0	62	5.0	34	18.2	125	10.1	70	14	12
21	10.0	69	5.1	35	19.2	132	10.7	74	16	17
29	11.3	78	5.5	38	19.4	134	10.1	70	13	19
37	9.1*	63	5.7	39	18.0*	124	11.3	80	19*	19
41	12.5*	86	6.9	48	15.4*	106	11.5	79	9	17
42	7.2	50	4.4	30	17.8	123	10.5	72	16	16
43	-	-	5.8	40	-	-	12.0	83	-	14

* Single data points

** Process Numbers (See Figure 6)

3 SHT + 25% red, RT + 700°F (371°C), 5 hrs + 1300°F (704°C), 10 hrs

7 SHT + 1300°F (704°C), 100 hrs + SHT + 25% red, RT + 1300°F (704°C) 5 hrs

13 SHT + 1300°F (704°C), 10 hrs + 25% red, RT + 1300°F (704°C) 5 hrs

21 SHT + 1300°F (704°C), 10 hrs + 25% red, 700°F (371°C) + 1300°F (704°C), 5 hrs

29 SHT + 1300°F (704°C), 10 hrs + 25% red, 1300°F (704°C) + 1300°F (704°C), 5 hrs

37 SHT + 1300°F (704°C), 10 hrs + 25% red, 1800°F (982°C) + 1300°F (704°C), 5 hrs

41 SHT + 25% red, RT + 1300°F (704°C), 5 hrs

42 SHT + 15% red, RT + 1300°F (704°C), 5 hrs

43 SHT + 1300°F (704°C), 100 hrs

SHT = Solution heat treat = 2200°F (1204°C), 1/2 hr, water quench

Red = Reduction by rolling expressed in % of original thickness

conditions, i. e. , 5/minute with a heating rate of 500°F/second (260°C/second) and a soaking time of 5 seconds. The processes listed above and the resulting data are shown by Table VII. The results showed no real benefit from the thermomechanical processing of VM-103. However, for comparison, L-605 specimens were tested under similar conditions (Table VII) and the solution treated VM-103 showed 40 percent higher yield strengths. The data indicated that although thermomechanical processing provides little or no benefit at these temperatures, solution treated VM-103 still appears attractive as a replacement for L-605 for various high temperature applications.

The final testing effort for Task I involved the generation of conventional and high strain rate tensile data on solution heat treated VM-103. Based on the results discussed above, solution heat treated VM-103 was selected and evaluated at 75, 1200, 1600, 1800, 2000 and 2200°F (24, 649, 871, 982, 1093 and 1204°C). The results are shown by Table VIII.

Task II Alloy Improvement

Background

Although VM-103 appeared very promising, the data indicated the possibility that slightly more exploratory development with respect to composition and impurity level could yield even a more promising alloy. It is also important to understand more fully the effects of impurities and compositional tolerances in order to ultimately write a procurement specification that can be met with minimum cost. Such information is also important as a basis for any other future superalloy development work.

So far, little attention had been paid to sulphur, potassium, manganese or silicon contents of VM-103, the philosophy being to keep these elements as low as possible on a best efforts basis. Earlier work on L-605 incicated that silicon aggravates an embrittling effect resulting from precipitation of a Laves phase (Co_2W) after prolonged exposure to 1600°F (871°C)[12, 13]. Because early NASA research and Contract NAS3-12421[3] work showed a similar aging phenomenon in VM-103, resulting primarily from Co_3W precipitation, the effects of silicon appeared worthy of investigation. Where short term properties are of particular interest the silicon content could be adjusted to take advantage of the increased mechanical properties.

Other data have shown possible beneficial effects of manganese with respect to fabricability of L-605. The manganese content of L-605 is specified as 1 to 2 percent, and published data, although inconclusive, indicated that the higher region of this range was desirable for increased fabricability[14]. The beneficial effect of manganese in steels is also well known and it was believed that similar effects might occur on the VM-103 alloy.

Wlodek[15] has indicated that high iron contents are beneficial in L-605 with respect to retarding long term embrittlement. NASA data have shown that iron stabilizes the face centered cubic to hexagonal transition, thereby reducing

TABLE VII

VM-103 HIGH STRAIN RATE TENSILE DATA

(Average of Triplicate Results)

Process Number**	0.2% Offset Yield Strength				Ultimate Tensile Strength				Elongation		Reduction in Area	
	2000°F(1093°C)		2200°F(1204°C)		2000°F(1093°C)		2200°F(1204°C)		2000°F(1093°C)	2200°F(1204°C)	2000°F(1093°C)	2200°F(1204°C)
	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	% in 1 in. (2.5 cm)	% in 1 in. (2.5 cm)	%	%
4	29.7	205	22.4	154	31.5	217	22.9	158	25	25	43	46
24	35.8	247	19.6	135	36.7	253	19.6	135	30	24	54	47
32	28.6	197	21.1*	145	31.6	218	22.0*	152	33	31*	61	60*
42	40.5	279	23.7*	163	42.0	290	23.7*	163	17	27*	35	42*
45	38.8*	268	25.7*	177	39.8*	274	25.7*	177	19*	20*	31*	39*
L-605	27.8	192	17.8	123	31.5	217	17.8	123	25	25	56	46

*Average of duplicate specimens

Process Numbers (See Figure 6)

4 SHT + 25% Red., RT + 1000°F(538°C), 5 hrs + 1300°F(704°C), 10 hrs

24 SHT + 1300°F(704°C), 10 hrs + 25% Red., 700°F(371°C) + 1600°F(871°C), 50 hrs

32 SHT + 1300°F(704°C), 10 hrs + 25% Red., 1300°F(704°C) + 1600°F(871°C), 50 hrs

42 SHT + 25% Red., RT + 1300°F(704°C), 5 hrs

L-605 2150°F (1177°C), 1/2 hr, Water Quenched

SHT = Solution heat treat = 2200°F(1204°C), 1/2 hr, Water Quench
Red = Reduction by rolling enpressed in % of original thickness

TABLE VIII

CONVENTIONAL AND HIGH STRAIN RATE TENSILE PROPERTIES OF SOLUTION HEAT TREATED[a] VM-103

(Average of Duplicate Specimens)

Test Temp.		Conventional Strain Rate[b]					High Strain Rate[c]				
		0.2% YS		UTS		Elongation % In 1 in. (2.5 cm)	0.2% YS		UTS		Elongation % In 1 in. (2.5 cm)
°F	°F	ksi	N/mm^2	ksi	N/mm^2		ksi	N/mm^2	ksi	N/mm^2	
75	24	102	703	159	1096	17	123	848	165	1138	22
1200	649	78	538	113	779	12	75	517	119	820	26
1600	871	58	400	82	565	3	70	483	105	724	12
1770[d]	966	43	296	60	414	2					
1800	982						57	393	68	469	19
2000	1093	20	138	22	152	10	39	269	40	276	19
2200	1204	6	41	10	69	11	26	179	26	179	20

[a] Solution heat treated = 2200°F (1204°C), 1/2 hour, water quench

[b] 0.005/minute to yield followed by 0.05/minute to failure

[c] 5 minutes to failure

[d] Equipment malfunction, tests conducted at approximately 1770°F (966°C) instead of 1800°C (982°C)

the tendency for hexagonal stacking faults which serve as nucleation sites for embrittling precipitates. NASA data have also indicated detrimental effects on cast VM-103 with iron and nickel in excess of 3 percent with respect to 1850°F (1010°C) stress rupture strength[16]. Based on this information it was considered that small iron or nickel additions on the order of 2 percent might be of value in retarding long term embrittlement without a sacrifice in short time high temperature properties.

Early NASA data showed slightly better mechanical properties resulting from inert atmosphere induction melting compared to vacuum melting. Differences in properties and fabricability resulting from vacuum arc remelting and electroslag remelting have also been observed. These effects indicate a possible gas content variation as a function of melting practice which may affect the properties of the alloy.

Scope

This task was designed to investigate the effects of melting techniques, impurities, and alloy additions on the fabricability and properties of the VM-103 alloy. This was to be accomplished by melting, processing and evaluating two series of heats designated as "A" and "B", each including the standard VM-103 composition and selected alloying additions.

Material, Series "A"

Three 5-10 pound (2.3 - 4.5 kg), 2 inch (5.1 cm) diameter heats were vacuum induction melted at Aeronutronic. The heats were designated as A1, standard VM-103 composition; A2, standard VM-103 composition plus 10 percent nickel; and A3, standard VM-103 composition plus 10 percent nickel and 5 percent iron. The target compositions were achieved with reasonable success, the chemical analyses of the ingots are presented by Table III. The iron loss during the melting of heat A3 was greater than anticipated, yielding only 4.1 percent instead of the target 5 percent.

The ingots were machined into round-corner-square configurations and hot rolled to 0.100 inch (0.25 cm) thick sheet using identical rolling schedules, as established under Contract NAS3-12421[3] and discussed in Section 3 of this report. The material was solution heat treated at 2200°F (1204°C) for one-half hour and water quenched after the hot rolling. The material was subsequently hot and cold rolled to provide 0.040 inch (0.1 cm) thick sheet with 0, 15, 25 and 40 percent cold work for tensile testing. Although all three heats could be cold reduced as much as 25 percent with no difficulty, the standard VM-103 composition heat, A1, showed edge cracking at cold reductions of about 40 percent. The nickel and iron additions improved both the hot and cold workabilities of the VM-103 alloy. In general the fabricabilities could be rated from best to poorest as A3, A2, and A1, respectively. The hardness data shown by Table IX as a function of cold work indicated that the two modified heats were considerably softer than the standard VM-103 composition, which correlates with their improved workabilities.

TABLE IX

HARDNESS OF VM-103 SHEET
AS A FUNCTION OF CHEMISTRY AND COLD WORK

Heat No.	Nominal Composition	Melting Process	Solution Heat Treated R_c	Cold Work		
				15% R_c	25% R_c	40% R_c
A1	Std. VM-103	VIM	34.5	47	48	49.5
A2	Std. VM-103 + 10% Ni	VIM	25	41	45	47
A3	Std. VM-103 + 10% Ni = 5% Fe	VIM	24	40	43	45
B1	Std. VM-103 + ~ .35 Si + ~ .35 Mn	VIM	33	46.5	49	52
B2	Std. VM-103 + 10% Ni + ~ .35 Si + ~ .35 Mn	VIM	27	30	43.5	48
B3	Std. VM-103 + 10% Ni	ESR	31	46	48	50.5
B4	Std. VM-103	ESR	35	48	50.5	52.5

Solution Heat Treat = 2200°F (1204°C), 1/2 hours water quench

VIM = Vacuum Induction Melted

ESR = Electroslag Remelted

Material, Series "B"

Four 5-10 pound (2.3 - 4.5 kg), 2 inch (5.1 cm) diameter heats were vacuum induction melted at Aeronutronic. The heats were designated as B1, standard VM-103 composition + 0.25-0.50 Si + 0.25-0.50 Mn; B2, standard

VM-103 composition + 10 percent Ni + 0.25-0.50 Si + 0.25-0.50 Mn; B3, standard VM-103 composition + 10 percent Ni; and B4, standard VM-103. The 2 inch (5.1 cm) diameter vacuum induction melted B3 and B4 material was electroslag remelted into 4 inch (10.2 cm) diameter ingots. All the ingots were conditioned for forging by O.D. machining and local grinding to remove minor surface impurifications. The "B" series material was forged to a 1 inch (2.5 cm) square bar using the techniques developed on Contract NAS3-12421[3] and discussed in Section 3, "Ingot Reduction." The B1 ingot showed the usual edge cracking but forged reasonably well. Heat B2 caused considerable difficulty during forging and was almost completely lost during subsequent hot rolling. The problems were partially attributed to porosity in the cast ingot; therefore, a new heat with the same nominal composition designated B2-2 (Table III) was melted. The ingot was machined to a round-cornered-square and hot rolled using the same parameters that were successful in processing the Series A heats. Nearly all of the material was lost due to breakup during rolling, indicating poor hot workability. However, sufficient quantities were salvaged for a partial evaluation. The electroslag remelted material, heats B3 and B4 forged very well with a 100 percent yield, thus again, indicating the superior hot workability of the electroslag remelted material.

The hardness as a function of cold work reported in Table IX indicated that the work hardening characteristics of the standard VM-103 composition were slightly reduced by the addition of 10% nickel as shown by a comparison of heats A1 and A2 and heats B3 and B4. This lowering effect was further accentuated by adding 10% nickel plus 5% iron, as shown by heat A3. Although the hardness values for heats B1 and B2 do not indicate any increase in the cold work hardening characteristics, these heats showed extremely poor fabricability during hot forging and rolling.

Evaluation

Chemistry

Samples from the various ingots were chemically analyzed for the alloying components of VM-103 as well as the elements used in the modified compositions. The metallic elements were analyzed by X-ray spectroscopy and the gas and carbon by vacuum techniques. The results, shown by Table III, indicate reasonable success in controlling composition during melting and casting the VM-103 alloy by induction and electroslag remelting. The effect of interstitial content on the VM-103 alloy was considered in the evaluation; however, no provisions were made to purposely increase the interstitial content of the various heats during the melting cycle. The chemistry results shown by Table III indicate that the various levels obtained were consistent from heat-to-heat and did not indicate any significant trends in the data.

Mechanical Properties

Tensile specimens were fabricated from each of the seven heats for testing in the following conditions:

Condition	Test Temperature	
	75°F (24°C)	2000°F (1093°C)
SHT	X	X
SHT + Aged	X	X
SHT + 25% Reduction	X	

SHT: Solution Heat Treated 2200°F (1204°C), 1/2 hour, water quench

Aged: 1300°F (704°C) 10 hours, air cool

25% Reduction: 25% Reduction at 75°F (24°C)

The results of the evaluation (Table X) showed a significant increase in ductility for heats A2 and B3 with the 10 percent nickel addition with only a small decrease in strength. No significant increase in tensile strength resulted from the additions of silicon and manganese to heats B1 and B2. Heats A1, B3 and B4 were selected for additional evaluation.

Task III Property Evaluation

Considerable data have been generated on VM-103, particularly short time tensile data as reported in NASA CR-72726[3]. For high temperature applications of the alloy, additional properties such as tensile strength, creep rupture, hardness, thermal expansion and thermal conductivity over the temperature range from 1200°F to 2000°F (649 to 1093°C) were required for design purposes.

Scope

The scope of this task was to determine additional design property data on standard and modified compositions of the VM-103 alloy. The standard composition and the 10 percent nickel modification were selected as the most promising alloys from Task II.

Material

The material required for this phase of the program was produced during the Alloy Improvement phase by the techniques discussed in Task II. Heat A1 induction melted standard VM-103 composition, heat B3 induction plus electroslag remelted standard VM-103 + 10% nickel composition and heat B4 electroslag remelted standard VM-103 were selected for evaluation. The chemical analysis of the three heats are presented in Table III.

TABLE X

MECHANICAL PROPERTIES OF STANDARD AND MODIFIED VM-103

Condition	Heat No.	Test Temp °F	Test Temp °C	0.2% Offset Yield Strength psi	0.2% Offset Yield Strength N/mm^2	Ultimate Tensile Strength ksi	Ultimate Tensile Strength N/mm^2	Elongation in 1 in. or 2.5 cm, %
SHT	A1	75	24	88.2	608	138.7	956	9.5
	A2	75	24	73.3	505	140.8	970	23.5
	A3	75	24	72.1	497	133.4	919	22.5
	B1	75	24	86.4	595	149.5	1030	17.5
	B2	75	24	76.6	527	144.7	997	27.3
	B3	75	24	76.5	527	156.2	1076	35.5
	B4	75	24	90.5	624	150.8	1039	15.0
SHT	A1	2000	1093	17.3	119	20.4	141	11.5
	A2	2000	1093	16.9	116	20.6	142	12.3
	A3	2000	1093	14.1	97	16.7	115	11.8
	B1	2000	1093	11.8	81	16.1	111	39.5
	B2	2000	1093	11.1	76	16.4	113	27.0
	B3	2000	1093	10.2	70	16.7	115	41.0
	B4	2000	1093	13.7	94	18.7	129	31.5
SHT + AGE	A1	75	24	144.4	995	174.8	1204	2.5
	A2	75	24	114.5	789	159.7	1100	11.7
	A3	75	24	86.2	594	133.1	917	13.0
	B1	75	24	149.9	1033	176.9	1218	5.0
	B2	75	24	129.4	892	177.7	1224	13.5
	B3	75	24	110.9	764	176.0	1213	13.2
	B4	75	24	133.1	917	167.2	1152	3.0
SHT + AGE	A1	2000	1093	12.5	86	19.3	133	23.5
	A2	2000	1093	11.6	80	17.3	119	30.5
	A3	2000	1093	11.5	79	17.4	119	30.5
	B1	2000	1093	10.6	73	17.1	118	46.0
	B2	2000	1093	10.2	70	15.6	107	35.5
	B3	2000	1093	10.5	72	16.1	111	33.5
	B4	2000	1093	13.2	91	19.6	135	22.0
SHT + 25% Red.	A1	75	24	152.9	1053	204.1	1406	4.3
	A2	75	24	172.8	1191	202.2	1393	5.3
	A3	75	24	170.2	1173	198.0	1364	5.0
	B1	75	24	150.9	1040	237.7	1638	2.8
	B2	75	24	154.7	1066	206.8	1425	5.8
	B3	75	24	166.3	1146	204.9	1412	10.0
	B4	75	24	165.7	1142	251.4	1732	2.5

SHT = Solution heat treat, 2200°F (1204°C), 1/2 hour water quench

AGE = 1300°F (704°C), 10 hours air cool

25% Red = 25% Reduction at 75°F (24°C

Heat Nos:
- A1 - Standard VM-103, (VIM)
- A2 - Standard VM-103 + 10% Ni, (VIM)
- A3 - Standard VM-103 + 10% Ni, (VIM)
- B1 - Standard VM-103 + ~ .35 Si + ~ .35 Mn (VIM)
- B2 - Standard VM-103 + 10% Ni + ~ .35 Si + ~ .35 Mn (VIM)
- B3 - Standard VM-103 + 10% Ni (ESR)
- B4 - Standard VM-103 (ESR)

Physical Properties

Thermal Expansion

The thermal expansion of a sample of induction melted standard VM-103 composition from heat A1 was determined with a standard Leitz Dilatometer using a 1.97 inch (50.00 mm) long specimen at a heating rate of 7°F/minute (4°C/minute) in a nitrogen atmosphere. The graph of percent expansion versus temperature shown by Figure 7 indicates almost linear behavior over the entire temperature range. The average coefficient of linear thermal expansion is 7.75×10^{-6}/°F (13.95×10^{-6}/°C) over the range of 77 to 1832°F (25 to 1000°C).

Density

The density of a sample from the above heat of material was determined by the displacement method. The density of induction melted, forged and hot rolled standard VM-103 was 0.357 lb/in^3 (9.89 g/cm^3).

Mechanical Properties

Tensile specimens from heats A1, B3 and B4 were tested in the following conditions:

Condition	Test Temperature				
	75°F (24°C)	1200°F (649°C)	1600°F (871°C)	1800°F (982°C)	2000°F (1093°C)
SHT	X	X	X	X	X
SHT + Age[(a)]	X				X
SHT + Age[(b)]	X		X		
SHT + 25% Red.	X				

SHT = Solution heat treat, 2200°F (1204°C), 1/2 hour water quench

Age[(a)] = 1300°F (704°C), 10 hours, air cool

Age[(b)] = 1600°F (871°C), 192 hours, air cool

25% Red. = 25% reduction at 75°F (24°C)

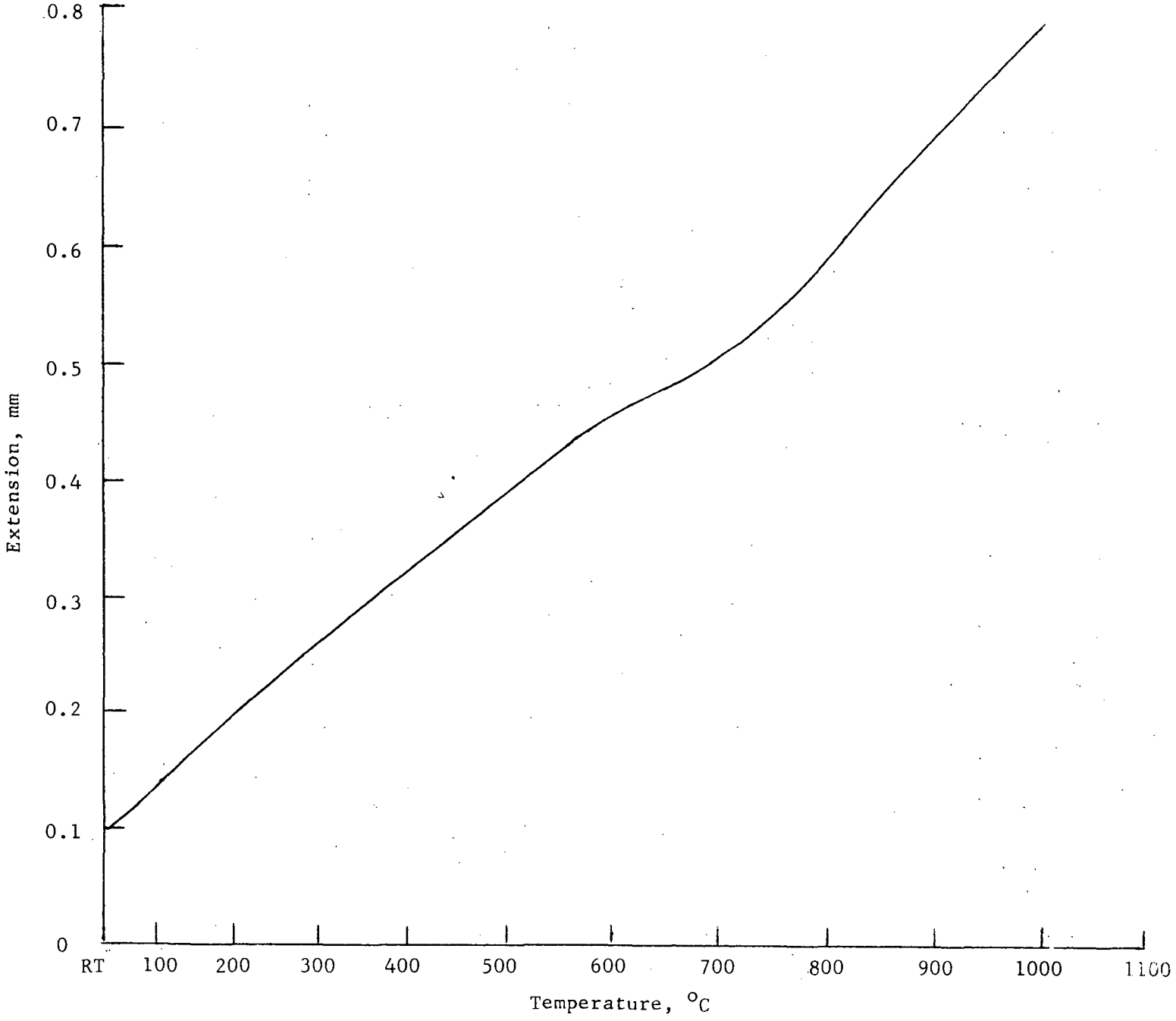


FIGURE 7. THERMAL EXPANSION OF VM-103

The results of the mechanical properties evaluation shown by Table XI confirmed the previous results obtained during Task II. The previous results for heats A1, B3 and B4 have been relisted for comparison. Heat B3 with the 10 percent nickel addition shown as increase in ductility with only a small decrease in tensile strength. The mechanical properties of solution heat treated material as a function of test temperature is shown by Figure 8. Solution heat treated samples from heats A1, B3 and B4 were encapsulated in evacuated glass tubes and exposed for 192 hours at 1600°F (871°C) and air cooled. Heat B3 with 10 percent nickel indicated a significant increase in ductility as measured by the room temperature elongation after the long term exposure in the 1600°F (871°C) embrittlement range compared to the standard composition VM-103, heats A1 and B4.

Hardness Testing

Samples from heats B3 and B4 in the conditions shown by Table XII were prepared for hot hardness testing at temperatures up to 1800°F (982°C). The samples, approximately 1/2 x 2.0 x 0.100 inch (1.2 x 5.1 x 0.23 cm) with ground surfaces, were evaluated in a standard Wilson hot hardness tester. The hardness values obtained for the B3 heat material with 10 percent nickel are slightly lower than for the standard VM-103 composition heat B4 and also lower than the vacuum induction melted material heat A2 reported earlier, with the same composition as heat B3. The hardness trends indicate that the hardening effects of cold work, and to a lesser extent the effects of aging, are retained reasonably well at temperatures up to 1400°F (760°C).

Impact Evaluation

Standard V-notch Charpy impact specimens were machined from heat B3 and B4 material in the conditions shown by Table XIII. Both heats were induction melted plus electroslag remelted. The solution treated condition of both heats showed the best impact strengths with drastic reductions in impact strength for the cold reduced material, increasing the transition temperature above ambient. Heat B3 with the 10 percent nickel exhibited better impact strength than the standard VM-103 composition in all conditions evaluated.

Creep Rupture

Wrought specimens from heats B3 and B4 and cast specimens from heat B3 were evaluated in creep rupture at 1600, 1800, 2000 and 2200°F (871, 982, 1093 and 1204°C) in a nitrogen atmosphere. The 2200°F (1204°C) tests were heated by induction heating of specimen and the lower temperature tests were performed with standard creep techniques with resistance furnace heating. The wrought specimens were machined from hot rolled, solution treated ESR material approximately 0.040 inch (1.0 cm) thick. The cast specimens were cast directly from an induction melt into a ceramic test specimen mold and subsequently solution heat treated. Figure 9 shows one of the castings.

TABLE XI

MECHANICAL PROPERTIES OF STANDARD AND MODIFIED VM-103 HEATS A1, B3 AND B4

(Average of Duplicate Specimens)

Condition	Heat No.	Test Temp		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation in 1 in. or 2.5 cm, %
		°F	°C	ksi	N/mm²	ksi	N/mm²	
SHT	A1	75	24	88.2	608	138.7	956	9.5
	B3	75	24	76.5	527	156.2	1076	35.5
	B4	75	24	90.5	624	150.8	1039	15.0
	A1	1200	649	79.9	551	109.4	754	9.0
	B3	1200	649	61.7	425	97.8	674	12.0
	B4	1200	649	85.1	586	101.2	697	4.8
	A1	1600	871	63.2	435	82.1	566	3.3
	B3	1600	871	48.4	333	52.4	361	10.8
	B4	1600	871	53.7	370	68.1	469	9.5
	A1	1800	982	33.7	232	47.6	328	22.5
	B3	1800	982	23.6	163	38.5	265	21.0
	B4	1800	982	27.9	192	41.9	289	32.0
	A1	2000	1093	17.3	119	20.4	141	11.5
	B3	2000	1093	10.2	70	16.7	115	41.0
	B4	2000	1093	13.7	94	18.7	129	31.5
SHT + AGE (a)	A1	75	24	144.4	995	174.8	1204	2.5
	B3	75	24	110.9	764	176.0	1213	13.2
	B4	75	24	133.1	917	167.2	1152	3.0
	A1	2000	1093	12.5	86	19.3	133	23.5
	B3	2000	1093	10.5	72	16.1	111	33.5
	B4	2000	1093	13.2	91	19.6	135	22.0
SHT + 25% Red.	A1	75	24	152.9	1053	204.1	1406	4.3
	B3	75	24	166.3	1146	204.9	1412	10.0
	B4	75	24	165.7	1142	251.4	1732	2.5
SHT + AGE (b)	A1	75	24	99.3	684	156.7	1080	1.5
	B3	75	24	80.5	555	127.5	878	4.7
	B4	75	24	92.4	637	155.4	1071	1.2
	A1	1600	871	48.0	331	77.3	533	10.5
	B3	1600	871	39.8	274	64.1	442	16.0
	B4	1600	871	51.4	354	80.6	555	10.8

SHT = Solution heat treat, 2200°F (1204°C), 1/2 hour water quench

AGE (a) = 1300°F (704°C), 10 hours, air cool

25% Red. = 25% reduction at 75°F (24°C)

AGE (b) = 1600°F (871°C), 192 hours, air cool

Heat Nos: A1 - Standard VM-103 (Vacuum Induction Method)
B3 - Standard VM-103 + 10% Ni (Electroslag Remelted)
B4 - Standard VM-103 (Electroslag Remelted)

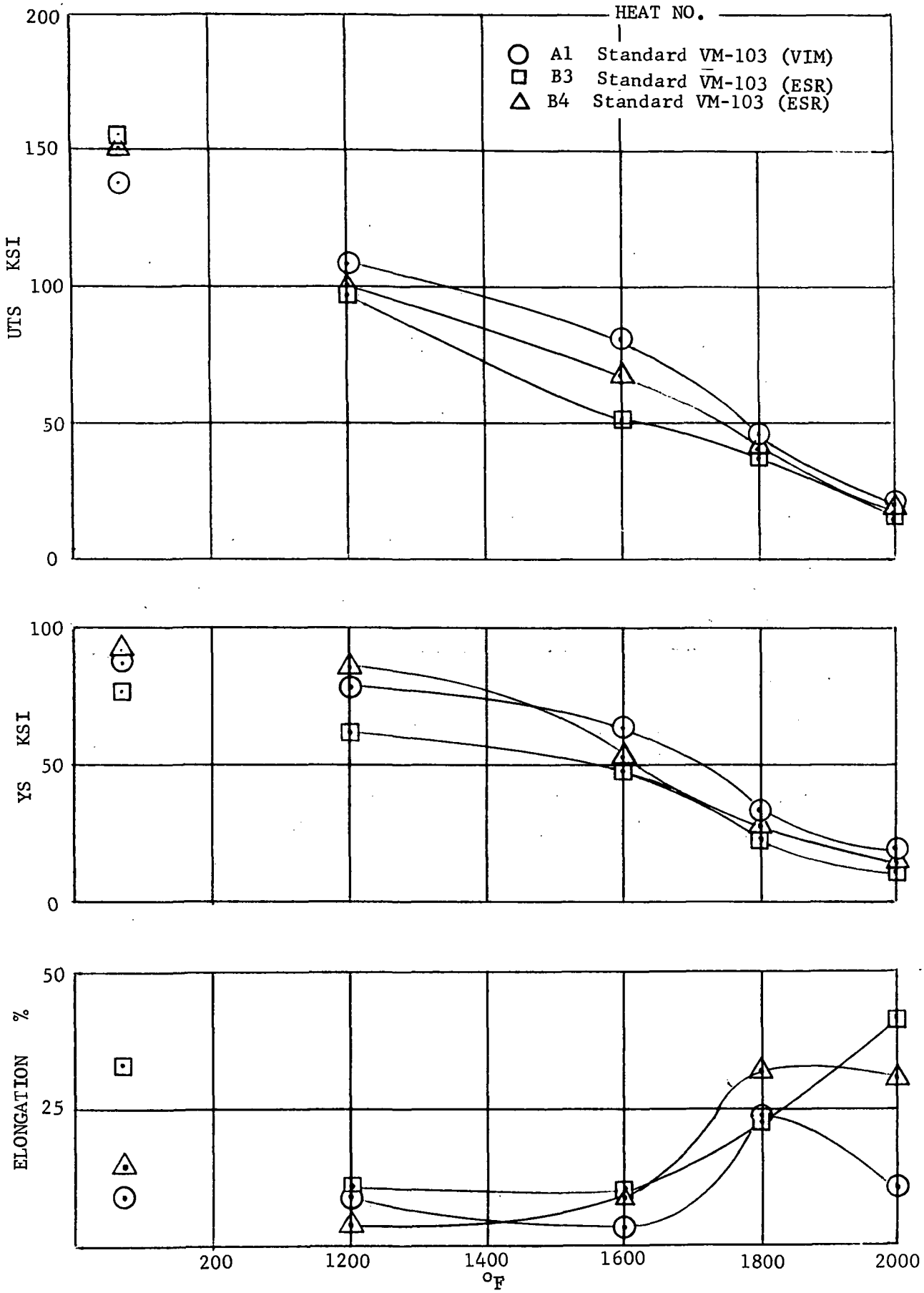


FIGURE 8. MECHANICAL PROPERTIES OF VM-103 AS A FUNCTION OF TEST TEMPERATURES

TABLE XII

HOT HARDNESS OF VM-103, HEATS B3 AND B4

Heat	Condition	Test Temperature			
		Ambient	1000°F (538°F)	1200°F (649°F)	1400°F (760°F)
B3	SHT	R_c 31	R_b 92	R_b 90	R_b 86
B4	SHT	R_c 38	R_b 96	R_b 95	R_b 92
B3	SHT + Age	R_c 35.5	R_b 99	R_b 98.5	R_b 86
B4	SHT + Age	R_c 42	R_c 35	R_c 30	R_b 100
B3	SHT + 25% Red.	R_c 48.5	R_c 41	R_c 39	R_c 31
B4	SHT + 25% Red.	R_c 49	R_c 48	R_c 43	R_c 29
B3	SHT + 25% Red. + Age	R_c 55	R_c 47	R_c 40.5	R_c 24
B4	SHT + 25% Red. + Age	R_c 54	R_c 47	R_c 41	R_c 28

Conditions:

SHT = Solution heat treat, 2200°F, 1/2 hour, water quench

Age = Age, 1300°F, 10 hours, air cool

25% Red. = 25% Reduction at 75°F (24°C)

Heat Nos: B3 - Standard VM-103 + 10% Ni (ESR)
B4 - Standard VM-103 (ESR)

TABLE XIII

IMPACT STRENGTH OF VM-103, HEATS B3 AND B4

Heat	Condition	Test Temperature			
		-65°F (-54°C)		75°F (24°C)	
		ft-lbs	Joules	ft-lbs	Joules
B3	SHT	27.1	36.7	30.4	41.2
B4	SHT	18.4	25.0	17.7	24.0
B3	SHT + Age	26.9	36.5	30.5	41.4
B4	SHT + Age	14.5	19.7	20.8	28.2
B3	SHT + 25% Red.	5.8	7.9	7.3	9.9
B4	SHT + 25% Red.	4.4	6.0	4.5	6.1
B3	SHT + 25% Red. + Age	5.3	7.2	2.7	3.7
B4	SHT + 25% Red. + Age	3.0[(a)]	4.1	1.7	2.3

Conditions:

SHT = Solution heat treated, 2200°F (1204°C), 1/2 hour, water quench.
Age = Age 1300°F (704°C), 10 hours, air cool
25% Red. = 25% reduction at 75°C (24°C)

(a) One specimen failed during machining

Heat Nos:

B3 Standard VM-103 + 10% Ni (ESR)
B4 Standard BM-103 (ESR)

FIGURE 9. VM-103 CREEP RUPTURE SPECIMENS CASTING

The results are shown graphically by Figure 10 and tabulated in Table XIV. The 10 percent nickel addition to heat B3 did not show any significant degradation of the creep rupture properties, particularly at the higher temperatures. The cast specimens exhibited higher creep rupture properties (Figure 11) than the wrought material.

Task IV, VM-103 Procurement Specification

The objective of Task IV was to prepare a specification for the procurement of wrought VM-103 products including material conditions restrictive requirements and quality control limits. The procurement specification generated during this task entitled, "Corrosion and Heat Resistant Alloy Bars, Forgings, Plate and Sheet - Cobalt Base - 25W-3Cr-1 Ti-0.5 Ar-0.5 C," is presented in Appendix A. The basic Aerospace Material Specification (AMS) format was utilized for this specification.

The approach for preparing this specification consisted of accumulating and reviewing the pertinent data from the various heats of VM-103 that were considered to be of highest quality. The information considered included compositional and purity variations, melting techniques, fabrication and processing parameters, mechanical properties and microstructure.

A comparison of data from three electroslag remelted heats, PF-11, PF-288 and B4 (Tables I and III) indicated that the compositional variations demonstrated by these heats had no significant effect upon mechanical properties or fabricability of wrought VM-103. This indicated that a rather broad range of compositional variations is acceptable for VM-103 and that specified tolerances typical of other wrought cobalt base alloys such as L-605 are also valid for the VM-103 alloy. Therefore, the composition tolerances specified in paragraph 3.1 (Appendix I) were purposely selected to be no more restrictive than AMS 5759 for L-605.

The various melting techniques utilized for the production of nickel and cobalt base superalloys have been evaluated during the several investigations of VM-103. The single vacuum induction melting technique used to produce several small heats provided material with acceptable properties but with fabricability definitely inferior to vacuum arc remelted or electroslag remelted material. Double vacuum melting processes are used for melting of commercial superalloys to achieve improved homogenity to reduce microsegregation and improve microcleanliness. These benefits were also shown for VM-103. The electroslag remelted VM-103 showed significant improvement in both ductility and fabricability over vacuum arc remelted material. Based on these results, vacuum induction plus VAR or ESR processes were specified.

The processing parameters presented in this specification were established by work performed on Contract NAS3-12421 as well as this contract. These processing parameters have repeatedly demonstrated that the specified mechanical properties, grain size and hardness requirements can be readily obtained.

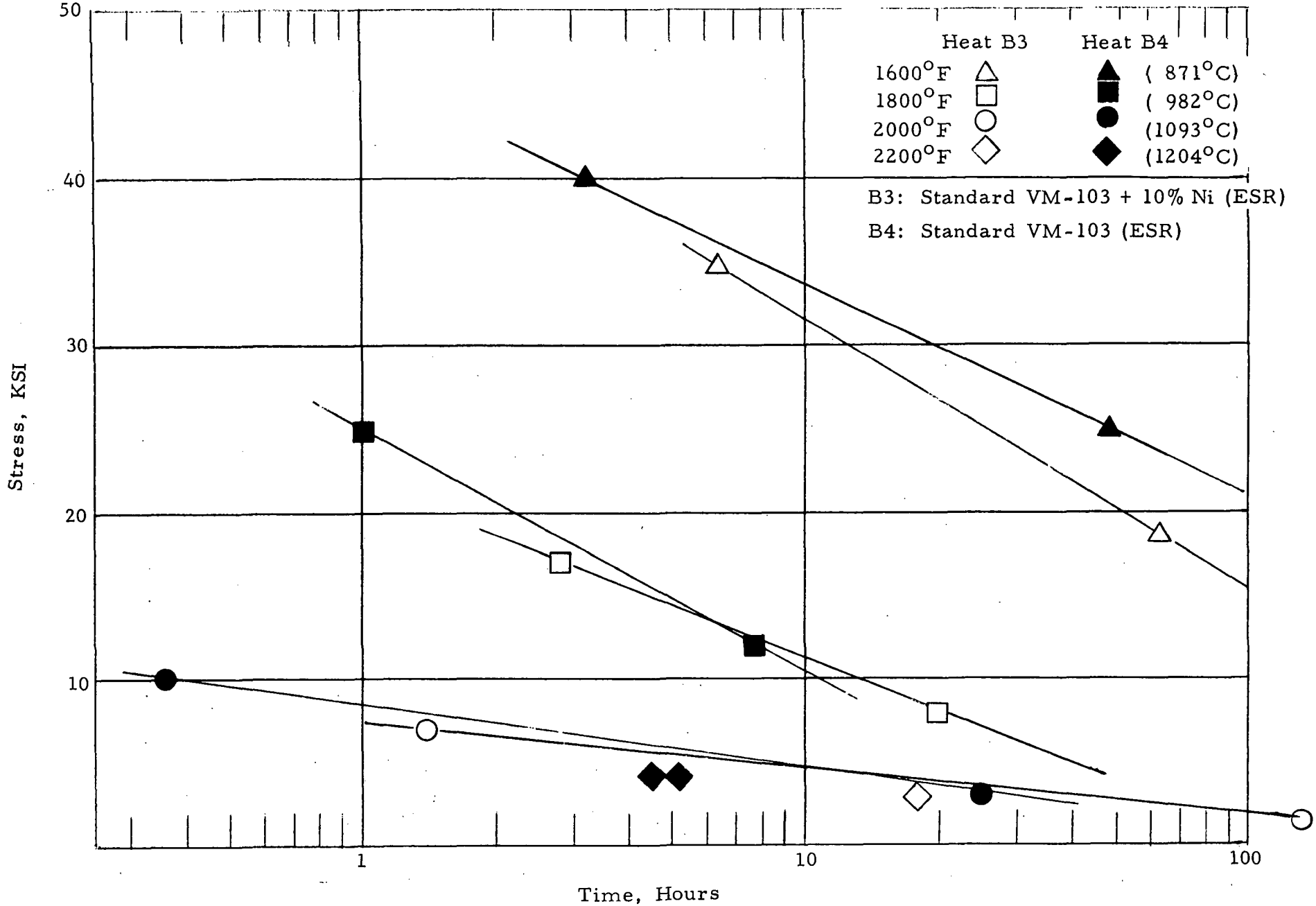


FIGURE 10. CREEP RUPTURE PROPERTIES OF WROUGHT VM-103

TABLE XIV

CREEP RUPTURE PROPERTIES OF WROUGHT AND CAST VM-103

Heat Number	Material Source[d]	Test Temperature		Applied Stress		Strain %						Rupture	
		°F	°C	ksi	N/mm²	1 Hour	5 Hours	10 Hours	20 Hours	50 Hours	100 Hours	Hours	Strain %
B3[a]	Wrought	1600	871	3.5	26	1.7	9.5					6.2	21.0
B3	Wrought	1600	871	18.5	127	0.15	0.4	0.6	1.2	4.6		63.5	12 0
B4[b]	Wrought	1600	871	40	276	2.4						3.3	5.5
B4	Wrought	1600	871	25	172	0.4	1.0	1.8	3.0			48.3	11.0
B3C[c]	Cast	1600	871	35	240	1.2	5.9					8.4	11 0
B3C	Cast	1600	871	20	137	0.05	0.15	0.3	0.5	1.0	1.6	132.5[e]	2.0[e]
B3	Wrought	1800	982	17	117	2.9						2.8	25.0
B3	Wrought	1800	982	8	55	0.1	0.5	1.8	17			20.0	17.0
B4	Wrought	1800	982	25	172	1.8						1.1	2.9
B4	Wrought	1800	982	12	83	1.0	6.1					7.7	18 0
B3C	Cast	1800	982	20	137	5.5						3.6	34.0
B3C	Cast	1800	982	15	103	0.95	4.8	9.5	17			28.6	31.0
B3	Wrought	2000	1093	7	48	14						1.4	31.0
B3	Wrought	2000	1093	1.5	10	0.15	1.6	3.8	8.0	2.0	48	105.6	65.0
B4	Wrought	2000	1093	10	69							0.6	42.0
B4	Wrought	2000	1093	3	26	1.1	5.0	15	50			20.5	54.0
B3C	Cast	2000	1093	12	83	3.6						3.6[e]	35.0[e]
B3C	Cast	2000	1093	7	48	0.15	0.65	1.3	2.5	6.2		78	10.0
B3	Wrought	2200	1204	2.8	19	3.8	8.1	16.0	29.4			18.2	40.2
B3													
B4	Wrought	2200	1204	4.1	28	0.9	5.2					5.3	5.4
B4	Wrought	2200	1204	4.1	28	0.8						4.4	5.6
B3C	Cast	2200	1204	6.7	46	13.2						2.7	37.0
B3C	Cast	2200	1204	4.2	29	1.3	5.2	7.3					

NOTES:
(a) Heat B3: Standard VM-103 + 10% nickel (VIM + ESR)
(b) Heat B4: Standard VM-103 (VIM + ESR)
(c) Heat B3C: Standard VM-103 + 10% nickel (VIM)
(d) All material solution heat treated, 2200°F (1204°C), 1/2 hour, water quenched
(e) Test terminated before failure

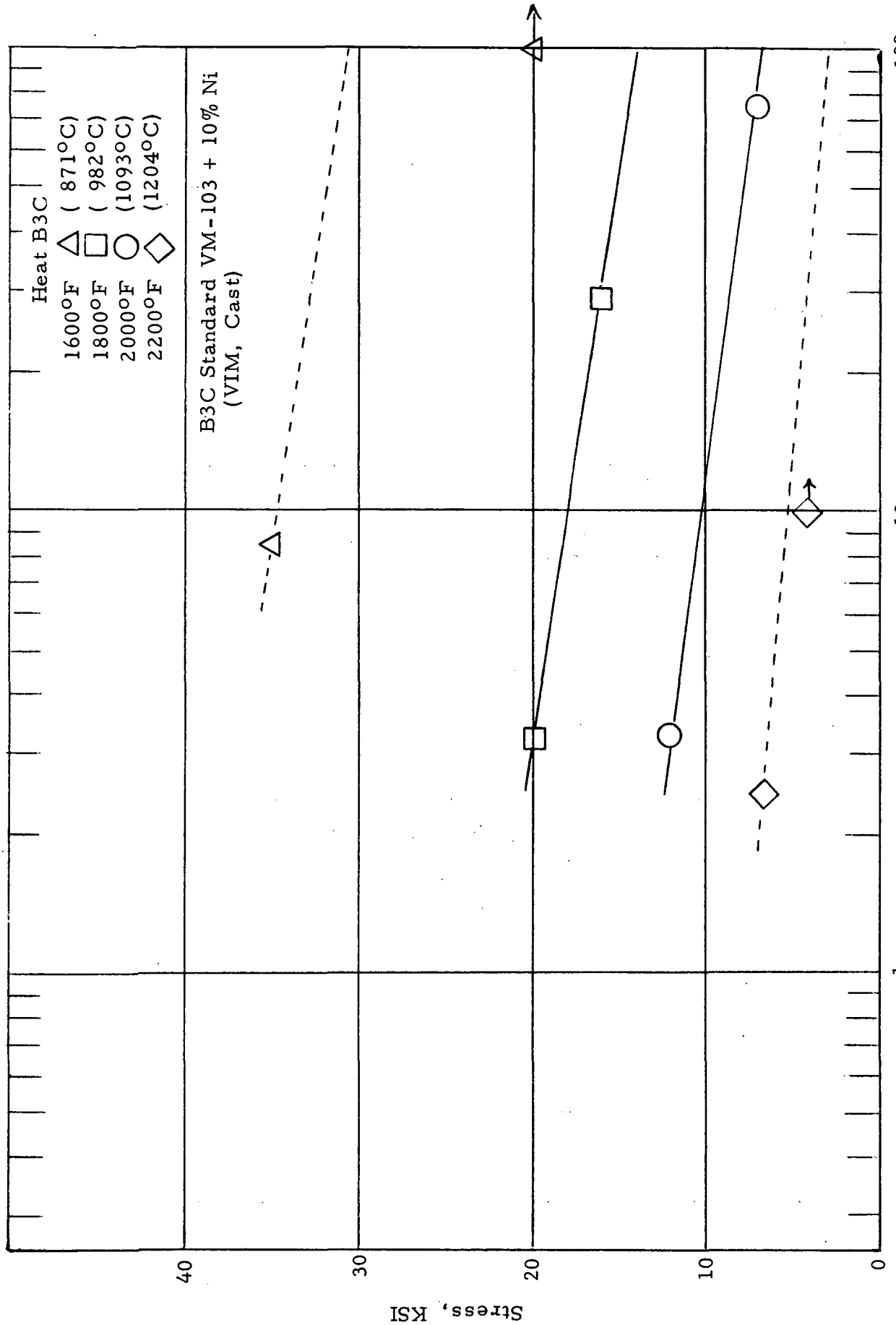


FIGURE 11. CREEP RUPTURE PROPERTIES OF CAST VM-103

4. SUMMARY OF RESULTS

The following major results were obtained from an investigation to develop a procurement specification for the NASA VM-103 alloy:

(1) The strength properties of VM-103 up to 2200°F (1204°C) and its fabricability make this alloy a useful alternate for conventional wrought cobalt and nickel base superalloys.

(2) The strength properties of VM-103 produced by vacuum induction melting and by vacuum induction melting plus electroslag remelting are essentially identical. Electroslag remelting significantly improves the fabricability and ductility of VM-103.

(3) The addition of 10 percent nickel to the standard VM-103 composition improves (a) ductility, (b) hot and cold fabricability, and (c) impact strength. The nickel addition is also effective in reducing the 1600°F (871°C) long term embrittlement characteristics of VM-103 without significantly reducing its tensile or creep rupture properties.

(4) Thermomechanical processing is very effective in increasing the room temperature hardness of VM-103 and probably its room and intermediate temperature strengths. Tensile tests conducted between 2000 and 2200°F (1093 and 1204°C) showed no beneficial effects.

5. CONCLUDING REMARKS

The development of VM-103 has progressed considerably as a result of two NASA contracts (NAS3-12421 and NAS3-14329) and internally funded work at Philco-Ford. Since 1968, the research status of VM-103 which primarily entailed characterization of 1700 g heats has progressed through fabrication and evaluation of 50 pound heats and development of an initial procurement specification for wrought VM-103 products. Composition, melting process, heat treating parameters, hot and cold working processes, physical and mechanical properties, and physical metallurgy of the alloy have been investigated to varying degrees. The alloy, in its present state of development, could be easily scaled up to production quantities of wrought or cast products.

In wrought form, VM-103 offers high temperature strength properties to 2200°F (1204°C) that exceed other widely used nickel and cobalt base alloys such as Rene 41 and L-605. This makes it attractive for hot gas valve components associated with guidance systems of various missile systems. Preliminary tests at Aeronutronic were encouraging on selected wrought components, and further testing has been recommended pending availability of additional developmental funding.

VM-103 has demonstrated considerable high temperature gas erosion resistance and thus shows potential as a liner for high performance barrels such as those associated with aircraft machine guns. VM-103 has already been tested and/or delivered to the Air Force for testing on three Air Force contracts. A fourth contract presently in progress also requires delivery of VM-103 lined test barrels, bringing the total to approximately 12 which includes both solution treated and 20% cold worked conditions. The alloy is well suited to this application, but lacks adequate machineability for large production quantities. Under Air Force funding, an electrochemical machining technique was successfully developed for rifling the alloy. Electrode discharge machining has been utilized successfully to gun drill VM-103, since conventional gun drilling is not economically attractive. A goal for future composition modifications should be to improve the machineability of VM-103.

The alloy appears to be very castable based on the results mentioned in this report, and previously reported by NASA and Philco-Ford. Again, the hot gas valve ducting and housings are obvious potential applications for cast VM-103 as well as various gas turbine engine components. Further development effort to more thoroughly characterize castability and cast properties would be useful.

As indicated, the 10% Ni addition to VM-103 significantly reduces the embrittling effect of prolonged exposure in the 1600°F (871°C) range which significantly extends the usefulness of the alloy. In addition, fabricability, ductility and impact strength are improved with little sacrifice in strength or creep rupture properties. Further studies to optimize nickel content in modified VM-103 appear worthwhile.

To summarize, VM-103 and/or modifications thereof appear to offer significant promise for existing and future aerospace and ordnance high temperature applications, and could be produced in production quantities with minimum scale-up efforts. It is believed that additional alloy modification studies would result in an alloy that is even more attractive.

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APPENDIX A

CORROSION AND HEAT RESISTANT ALLOY BARS, FORGINGS, PLATE AND SHEET - COBALT BASE - 25W - 3Cr - 1 Ti - 0.5 Zr - 0.5 C

1. Scope

The purpose of this specification is to establish material conditions, restrictive requirements and quality control procedures for VM-103 cobalt base forging stock, bars plate, and sheet. VM-103 is primarily for parts and assemblies that require service temperature up to 2200°F (1204°C).

2. Applicable specifications and standards, of the issues in effect on date of invitation for bids, or as stated on the purchase order, form a part of this specification.

2.1 AMS 2261; Tolerances - Nickel, Nickel Base and Cobalt Base Alloy Bars and Forging Stock.

2.2 AMS 2262; Tolerances - Nickel, Nickel Base and Cobalt Base Alloy Sheet, Strip and Plate.

2.3 AMS 2269; Chemical Check Analysis Limits, Wrought Nickel and Nickel Base Alloys.

2.4 AMS 2630; Ultrasonic Inspection.

2.5 ASTM E-45; Recommended Practice for Determining the Inclusion Content of Steel.

2.6 ASTM E-112 - Methods for Estimating the Average Grain Size of Metals.

2.7 Federal Test Method Standard No. 151a - Metals; Test Methods.

3. Technical Requirements

3.1 Composition - The composition of the alloy shall conform to the following:

	Min	Max
Tungsten	24	26
Chromium	2.5	3.5
Titanium	0.75	1.25
Zirconium	0.4	0.6
Carbon	0.48	0.52
Iron	-	0.1
Cobalt	Balance	

Check Analysis: Composition variation shall meet the requirements of the latest issue of AMS 2269.

3.2 Melting Practice - Material shall be produced by vacuum induction melting plus vacuum arc remelting or vacuum induction melting plus electroslag remelting.

3.3 Forging Practice - Forging parameters shall be chosen such that following solution heat treatment the forgings shall meet the requirements of Sections 3.6, 3.7, 3.8, 3.9, and 3.10. Ingots shall be reduced sufficiently in cross section to assure proper uniform refinement of structure in the forged billet.

3.4 Heat Treatment - All material shall be solution treated by heating at 2200 ± 25°F (1204 ± 14°C), holding at temperature for 1/2 hour and quenching in agitated water. These parameters may be varied as required to meet requirements of Sections 3.6, 3.7, 3.8, and 3.10.

3.5 Condition - All material shall be supplied in the solution heat treated and descaled condition.

3.6 Hardness - The material shall have a hardness not higher than Brinell 363 or equivalent.

3.7 Tensile Properties - Minimum tensile properties in the solution annealed condition shall be:

Tensile Strength	135,000 psi	(960 MN/mm^2)
Yield Strength, 0.2% offset	80,000 psi	(550 MN/mm^2)
Elongation, % in 4D	7%	

3.8 Grain Size - The grain size as determined by ASTM E-112 shall be predominantly number three of finer with occasional grains as large as number one permissible.

3.9 Macrostructure - Flow line patterns of forged parts shall be as specified on the forging drawing.

3.10 Microcleanliness - The procedure for determining the inclusion rating shall be in accordance with ASTM E-45, Method D. This rating based on specimens representing the worst area of inclusions shall not exceed the following:

	Inclusion Rating			
Type Inclusion	A	B	C	D
Thin	1.5	1.5	1	2
Thick	1	1	1	1.5

In addition, the material shall be substantially free of grain boundary precipitates when examined at 500X magnification after electrolytically etching with a solution of the following proportions: 100 ml H_2O, 40 ml acetic acid, 40 ml HCl, 15 ml H_2SO_4, 40 ml HNO_3, and 25 g $FeCl_3$.

3.11 Ultrasonic Inspection. - The method of ultrasonic inspection shall be by the immersion process in accordance with AMS 2630. All material (100 percent) shall be inspected to the discontinuity indication limits of 3.11.1, 3.11.2, 3.11.3, and 3.11.4.

3.11.1 No discontinuity indications shall be in excess of the reponse obtained from a 3/64-inch diameter, flat-bottomed hole located at the depth of the estimated discontinuity.

3.11.2 Multiple indications in excess of the response from a 1/32 inch diameter flat-bottomed hole located at the depth of the estimated discontinuity shall not have centers closer than one inch.

3.11.3 Indications from a single discontinutiy equal to or greater than the response from a 1/32 inch diameter flat-bottomed hole at the estimated discontinutiy depth shall not be more than one inch in length.

3.11.4 Multiple indications shall not be of such size or frequency as to reduce the back reflection pattern to 50 percent or less of the back reflection pattern of normal material of the same geometry, with the crystal parallel to the front and back surfaces to insure that the loss of back reflection is not caused by surface roughness or part geometry variation.

3.12 Workmanship - The material shall be uniform in quality and condition, free from pipe, flakes or heat cracks. It shall be free of defects such as seams, laps, cracks, slag, hard spots, porosity, rolled in scale, fissures, gas cavities, and undue segregation which may be detrimental to the fabrication or performance of parts.

4. Identification

Material shall be identified as indicated on the purchase order.

5. Quality Assurance

5.1 Lot - A lot is defined as all material produced in one run from the same heat of material and heat treated in the same furnace load.

5.2 Chemical Analysis - A sample from each heat of material represented in the shipment shall be analyzed to determine conformance to the chemical composition requirements of Section 3.1.

5.3 Tensile Properties

5.3.1 Two each room temperature tensile tests shall be made in accordance with Federal Test Method Standard 151 on each each lot represented in the shipment.

5.3.2 The test specimens shall be generated from coupons, as specified on the purchase order or applicable drawing.

5.4 Micro-Examination - One sample from each lot shall be prepared and examined to determine grain size and microcleanliness.

5.5 Hardness - Each lot shall be checked for hardness.

6. Reports

Unless otherwise specified, the vendor of the product shall furnish with each shipment three copies of a report of the results of tests for chemical composition of each heat in the shipment and the results of tests on each size heat to determine conformance to the technical requirements of this specification. This report shall include the purchase order number, material specification number, heat number, size, and quantity from each heat. If forgings are supplied, the part number and size of stock used to make the forgings shall also be included.

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