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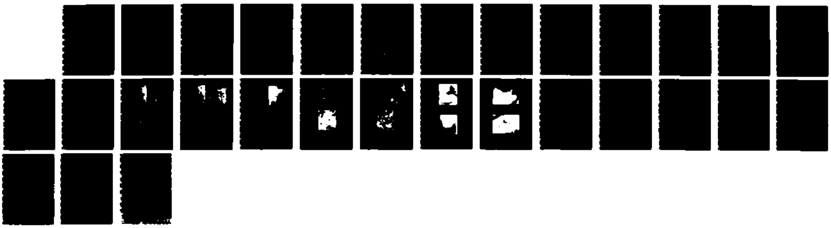

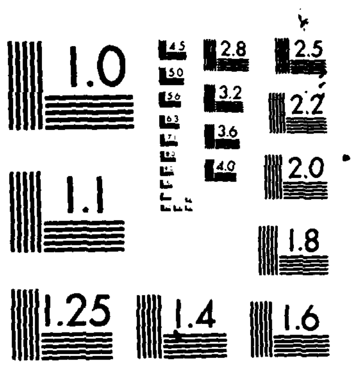

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MECHANICAL PROPERTY CHARACTERIZATION OF VASCOMAX T-250

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July 1986

US ARMY
LABORATORY COMMAND
MATERIALS TECHNOLOGY
LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
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ABSTRACT

This report addresses a mechanical property characterization of VascoMax T-250 in the form of a 3-inch-diameter forged bar. Data were generated for aging temperatures of 850, 900, and 950°F and for aging times of 3, 4, and 8 hours. Parameters addressed were hardness, tensile properties, Charpy V-notch impact energy and fracture toughness. Microstructural aspects were also addressed.

Results indicate that for the heat treatments investigated the tensile strength increases with increasing aging temperature and time. Fracture toughness (K_{IQ}) increases with aging temperature, and Charpy energy is the highest in the 950°F aged condition. Based on these findings the 950°F aging temperture results in the maximum tensile strength and toughness properties for the material in 3-inch-diameter bar form. Discrepancies in some of the tensile strength data and tensile fracture appearances are attributed to exogenous inclusions peculiar to this heat.

(K sub IQ)

CONTENTS

BACKGROUND AND INTRODUCTION

The cobalt-containing 18% Ni maraging steels were developed by the International Nickel Company (INCO) during the early 1960's.[1] Four tensile strength levels (grades) were developed, namely 200, 250, 300, and 350 ksi, with each grade differing principally in its level of titanium and cobalt. These steels, especially the 250 and 300 grades, have received rather wide use in production tooling, aerospace, and military applications. Relative to the latter, the 300 grade has been used extensively as a missile motor case material in the TOW and Stinger systems. This grade contains between 8.5 to 9.5 w/o cobalt.

In the late 1970's cobalt became a critical and strategic element to the United States, creating the need to minimize our foreign dependency by way of alloy modification. In 1980 INCO developed a cobalt-free version of the 18% Ni maraging steels. The initial alloy had relatively poor toughness properties but INCO felt that a better composition could be defined. They then entered into a program with Teledyne Vasco and the alloy designated as VascoMax T-250 was developed. The basic difference between this alloy and the existing 250 grade maraging steel is that the former is cobalt-free and contains more titanium and less molybdenum than the latter. Teledyne Vasco is now producing this alloy in full scale production heats and it is the material which is addressed in this report.

The Marquardt Company, Van Nuys, CA, under contract from the U.S. Army Missile Command (MICOM) has been the sole producer of TOW flight missile cases. In 1981 MICOM funded the Marquardt Company to explore the use of VascoMax T-250 as a replacement for the 300 grade 18% Ni maraging steel in the TOW flight case.[2] As of this date, based primarily on proof testing by the Marquardt Company, hot gas burst testing by MICOM, and mechanical property evaluations,[3-5] MICOM has approved VascoMax T-250 for use in the TOW flight missile case.

Irrespective of the above, it was the belief of both MTL and some MICOM personnel that VascoMax T-250 needed to be more fully characterized in bar stock, plate and in final fabricated forms. Thus, an effort was initiated in FY83 using 6.2 funds, both in-house at MTL and by way of contract to MICOM, to provide a thorough metallurgical characterization of this material. In FY84 the MTL Advanced Development for Standardization Program (6.3 funding) was initiated. This program was a joint MTL/MICOM venture which addressed VascoMax T-250 as a material substitution in systems such as the Stinger flight missile case.

To this end this report deals with an aging response study, the first phase of the MTL effort. Parameters addressed include hardness, tensile properties, Charpy impact energy, fracture toughness and microstructure as a function of aging temperature and time. Future MTL work will address aging kinetics, stress corrosion and a metallurgical characterization of this material in both plate and in the final fabricated Stinger flight missile case form.

1. Source Book on Maraging Steels, Raymond F. Decker, ed., ASM, Metals Park, Ohio, 1979.
2. LAMPSON, F. K., and WOOD, J. L. *Fabrication and Delivery of Cobalt Free (Free-Co) Maraging Steel Rocket Motor Components.* The Marquardt Company, Van Nuys, CA, TR RK-CR-83-1, October 1982. Prepared for the U.S. Army Missile Command.
3. HENRY, R. J. *New Concepts in Maraging Steels.* Presented at WESTEC '82, Los Angeles, CA, March 25, 1982.
4. LAMPSON, F. K., and CROWNOVER, W. *Cobalt-Free Maraging Steel - - A New Development For Rocket Motor Case.* Presented at the Joint Army Navy NASA Air Force Interagency Propulsion Committee (JANNAF) Meeting, 1983.
5. LAMPSON, F. K. *Manufacturing Methods Interim Report For Cobalt-Free (Free-Co) Maraging Steel Rocket Motor Components.* The Marquardt Company, Van Nuys, CA, TR RK-CR-83-14, August 1983. Prepared for U.S. Army Missile Command, Contract No. DAAH01-81-C-B084.

MATERIALS AND TESTING PROCEDURE

The material used in this study was induction vacuum melted (IVM) into a 17-inch-diameter electrode and then consumable vacuum melted (CVM) into a 20-inch-diameter ingot. The ingot was homogenized and pressed to 6-inch billets and then rolled to 3-inch-diameter bars. Bars were then double annealed at 1700 and 1500°F. The material was produced by Teledyne Vasco and supplied to MTL by MICOM in the form of two 18 inch lengths of 3-inch-diameter bar stock. Both bars were from Heat No. R6251, which was melted in 1980. The MTL and Teledyne Vasco chemical analyses are shown in Table 1.

Table 1. CHEMICAL COMPOSITION

Heat No. R6251	Weight Percent C	Mn	P	S	Si	Ni	Co	Mo	Ti	Cr	Al	Cu
MTL	0.004	0.02	0.002	0.001	0.05	18.95	0.013	2.9	1.39	0.03	0.18	--
Teledyne Vasco	0.008	0.03	0.005	0.001	0.06	18.29	0.01	3.00	1.30	--	0.11	0.02

Hardness, tensile, standard Charpy impact and fracture toughness data were obtained as a function of aging temperature and time. Specimens were machined to blank form, heat treated and then finished machined. Blanks were solution annealed at 1500°F for 1 hour and then aged. Aging temperatures of 850, 900, and 950°F for times of 3, 4, and 8 hours were selected.

Tensile data were obtained using 0.252-inch-diameter button head, 0.252-inch-diameter threaded, and 0.160-inch-diameter threaded type specimens. A crosshead speed of 0.005-inch/min was used in the testing of all specimens. Standard 0.394-inch cross section Charpy V-notch specimens were used in generating impact energy data. Precracked Charpy type specimens were used in obtaining the fracture toughness data (K_{IQ}). K_{IQ} is a conditional plane strain (K_{IC}) value and is obtained from the load-deflection curves for each specimen using the conventional stress intensity factor calculations for 3-point bending. Microstructures for each heat treatment were also obtained.

RESULTS

Hardness

Rockwell C hardness (HRC) results are tabulated in Table 2 as a function of aging temperature and time. Hardness increases slightly as a function of aging time at 850°F from 49.4 to 50.8 HRC, however aging time does not have any significant effect at 900 or 950°F. Maximum hardness, approximately 51.5 HRC, was obtained with the 900°F aging treatment.

Tensile Properties

Tensile data from the 0.252-inch-diameter button head type specimen are tabulated in Table 3 as a function of aging temperature and time for the longitudinal orientation. Transverse tensile data for the 900°F aging temperature for the investigated times are also included. Yield and tensile strength increase as a

Table 2. EFFECT OF HEAT TREATMENT ON HARDNESS OF VASCOMAX T-250

Aging Temp °F	Aging Time Hrs	Hardness HRC
850	3	49.4
	4	49.8
	8	50.8
900	3	51.3
	4	51.7
	8	51.4
950	3	50.8
	4	50.5
	8	50.8

Table 3. EFFECT OF HEAT TREATMENT AND ORIENTATION ON THE TENSILE PROPERTIES (0.252-INCH-DIAMETER BUTTON HEAD SPECIMEN) OF VASCOMAX T-250

ORIENTATION	AGING TEMP °F	AGING TIME, HRS											
		3				4				8			
		TENSILE PROPERTIES											
		0.2%YS KSI	UTS KSI	ELON %	RA %	0.2%YS KSI	UTS KSI	ELON %	RA %	0.2%YS KSI	UTS KSI	ELON %	RA %
LONG.	850	-(1) -(1)	232 228 230	14.0 15.2 14.6	58.4 57.8 58.1	229 226 228	242 238 240	14.0 14.0 14.0	55.8 56.4 56.1	-(1) 236 236	253 251 252	14.0 14.0 14.0	57.8 58.4 58.1
	900	236 232 231	247 245 246	14.0 14.0 14.0	56.8 57.1 57.0	-(1) -(1)	254 255 255	14.0 14.0 14.0	59.8 59.1 59.5	-(1) 247 247	257 255 256	14.0 14.0 14.0	59.8 60.1 60.0
	950	234 240 237	253 252 253	14.1 12.8 13.5	59.8 60.3 60.1	241 250 246	251 261 256	14.0 14.0 14.0	60.7 57.5 59.1	249 247 248	261 259 260	14.0 14.0 14.0	61.7 60.8 60.3
TRANS.	900	230 -(1) 230	243 245 244	13.7 13.7 13.7	54.4 52.5 53.5	243 — 243	254 256 255	11.3 12.8 12.1	52.5 54.7 53.6	248 — 248	255 255 255	12.8 11.0 11.9	54.7 54.7 54.7

1. No value due to recorder mulfunction

function of both aging temperature and time. There is, however, a much greater effect of aging time on tensile strength following the 850°F aging temperature than for either the 900 or 950°F condition. For example, the tensile strength increases from 230 to 252 ksi as the aging time increases from 3 to 8 hours for the 850°F treatment, whereas the increase is 253 to 260 ksi for the 950°F aging temperature. This result indicates that 850°F is an underaging temperature for a 3 to 4 hour holding time. Also, there is little difference in tensile ductility as a function of aging temperature or time. Relative to specimen orientation for the 900°F aging treatment, there is no significant effect other than slightly lower transverse tensile ductility properties. The tensile data obtained from the 0.252 and 0.160-inch-diameter threaded type specimen are tabulated in Tables 6 and 7, which will be discussed later.

Modulus of Elasticity

Strain gages were used to measure the static modulus of elasticity. The average value for the longitudinal specimens was 26.3 X 10^6 psi with the values ranging from 25.1 X 10^6 to 27.0 X 10^6 psi. Transverse values ranged from 24.7 X 10^6 to 26.5 X 10^6 psi with the average being 25.7 X 10^6 psi. Based on these findings there appears to be little effect of orientation on the static elastic modulus for this material. It is interesting to note though that the lowest modulus for both orientations was from the 850°F 3-hour heat treatment.

Charpy Impact Energy

Charpy impact energy data for the investigated parameters are tabulated in Table 4. An examination of the results indicates that the Charpy energy increases as a function of aging temperature. Specifically, longitudinal values for a 3 hour aging time at 850, 900, and 950°F are 20.0, 22.1, and 27.0 ft-lb, respectively. Longitudinal values are higher than transverse values for all of the 900°F conditions. For the three aging times at 900°F, values for the transverse orientation are 18.6, 20.1, and 19.7 ft-lb, respectively.

Fracture Toughness

Fracture toughness data for the investigated heat treatment parameters are contained in Table 5. Because of non-conformance with ASTM E-399 test criteria these values are reported as K_{IQ} and not K_{IC}. As shown, three tests were run for each condition. The reason most of the data cannot be expressed as K_{IC} is that the specimen did not meet dimensional requirements.[6]

In addressing the data it is shown that K_{IQ} increases with increasing aging temperature. Average values for a 3 hour aging time at 850, 900, and 950°F are 88.5, 93.4, and 106.2 ksi$\sqrt{in.}$, respectively. K_{IQ} values decrease as function of aging time for the 850°F LR and 900°F TR orientation, with no significant change for the 900 and 950°F LR conditions. Relative to the effect of orientation, the fracture toughness is lower for the 900°F LR 3 hour condition and higher for 4 and 8 hour aging times than for similarly heat treated TR specimens.

Microstructure

Microstructures, Figures 1 through 3, were obtained for all heat treatment conditions. All samples exhibit an ASTM grain size of 8 and contain randomly dispersed precipitates. The material aged at 850°F for 3 and 4 hours etches lighter than that aged at the same temperature for 8 hours. Also, all material aged at 850°F etches lighter than that aged at 900°F for 3, 4, or 8 hours. The microstructures from samples aged for various times at 900°F etch uniformly, and are difficult to distinguish from each other. Martensite laths are accentuated by aging at 950°F for 3, 4, or 8 hours, although it is not as obvious for the latter time. Explanations are not offered for these differences in microstructural response as a function of aging time and temperature because a more sophisticated examination is necessary to adequately address this behavior.

6. BROWN, W. F., Jr., and SRAWLEY, J. E. *Plane Strain Crack Toughness Testing of High Strength Metallic Materials.* ASTM STP 410, 1966.

Table 4. EFFECT OF HEAT TREATMENT AND ORIENTATION ON THE CHARPY IMPACT ENERGY OF VASCOMAX T-250

ORIENTATION	AGING TEMP °F	AGING TIME, HRS. 3	4	8
		IMPACT ENERGY, FT-LB		
LONG.	850	21.1 20.9 20.0	23.6 23.3 23.5	21.9 20.8 21.4
	900	22.7 21.4 22.1	22.0 23.1 22.6	21.5 21.4 21.5
	950	26.5 [1] 27.4 [1] 27.0	28.7 [2] 28.7 28.7	27.8 27.5 27.7
TRANS.	900	17.2 19.9 18.6	21.3 18.9 20.1	20.9 18.5 19.7

1. Specimen notch depth of 0.311 inch
2. Specimen notch depth of 0.312 inch

Table 5. EFFECT OF HEAT TREATMENT AND ORIENTATION ON THE FRACTURE TOUGHNESS OF VASCOMAX T-250

ORIENTATION	AGING TEMP. °F	AGING TIME, HRS 3	4	8
		FRACTURE TOUGHNESS KQ, KSI$\sqrt{IN}$		
LR	850	90.6[1,2] 87.0[1] 82.4[1] 88.5	85.4[1] 82.4[1] 83.0[1.3] 83.6	77.0[1] 71.3[1] 74.4[1] 74.2
	900	95.3[1,2] 97.3[1,2] 87.5[1,2] 93.4	93.7[1] 100.4[1] 96.8[1] 96.7	97.7[1] 96.8[1] 93.2[1] 95.9
	950	107.3[1] 106.7[1] 104.7[1] 106.2	105.3[1] 105.8[1] 108.6[1] 106.6	106.7[1] 104.3[1] 104.8[1] 105.3
TR	900	97.3[1.2] 114.8[1.2] 101.2 104.4	106.4[1.2] 83.3[1] 80.9 90.2	80.9[1] 93.3[1] 95.1 89.9

Invalid K_{IC} due to the following:

1. Specimen size < $2.5\left(\frac{K_Q}{YS}\right)^2$
2. Crack length differs >10% of average
3. Crack width to specimen width ratio $\left(\frac{a}{w}\right)$ not within 0.45 to 0.55

DISCUSSION

Alloy Heterogeneity

As noted in Table 3, yield strength data could not be obtained for some of the investigated conditions due to a malfunction of the recorder. Thus, to fill in these gaps, and to generate more transverse tensile data, additional tests were conducted using the standard threaded 0.252-inch-diameter type tension specimens. This group of specimens was heat treated in an air atmosphere furnace. The results of these tests are tabulated in Table 6. In comparing the data of Table 3 and Table 6 it can be seen in the latter that (1) tensile ductility is significantly lower for the 850°F aging conditions, (2) the strength properties are higher for the longitudinal 850 and 900°F 3 hour condition, and (3) the tensile elongation is consistently lower for all investigated conditions. The significant difference cited for the 850°F condition was of great concern to the authors and an extensive investigation was conducted in an attempt to provide an explanation. The investigation will now be addressed.

Table 6. EFFECT OF HEAT TREATMENT AND ORIENTATION ON THE TENSILE PROPERTIES (0.252-INCH-DIAMETER THREADED SPECIMEN) OF VASCOMAX T-250

ORIENTATION	AGING TEMP. °F	AGING TIME HRS	0.2% YS KSI	UTS KSI	ELON %	RA %
LONG	850	3	234 235 235	248 250 249	32.3 30.2 31.3	7.3 7.6 7.5
		8	240	255	45.5	9.3
	900	3	244 242 243	257 256 257	63.1 63.1 63.1	10.9 11.4 11.2
		4	244 243 244	257 257 257	62.5 62.9 62.7	12.0 11.0 11.5
		8	247	258	63.0	11.6
	950	3	238 239 239	250 251 251	64.4 63.5 64.0	11.9 11.8 11.9
TRANS.	850	3	235 233 234	247 248 248	23.8 35.2 29.5	6.9 8.5 7.6
	900	3	241 243 242	255 255 255	57.0 58.1 57.6	10.6 9.9 10.3
	950	3	238 240 239	250 250 250	58.9 57.9 58.4	11.2 11.1 11.2

Microstructures were the first consideration when mechanical property differences were observed between similarly heat treated threaded and button head tensile specimens. Microstructures from samples in which such differences were observed are presented in Figures 4 and 5, where the same trends mentioned in the results with respect to aging temperature and time are seen. Further, Figures 4 versus 5 reveal that the button head samples have slightly larger grain sizes (less than one ASTM grain size number) than similarly heat treated threaded samples. Also, the button head samples took much longer to etch than the threaded samples. A potential explanation for this was a chemical composition difference, however, chemical analyses were run on samples from which the microstructures were obtained and no such difference was observed. It could not be verified that these observed differences in microstructure accounted for the magnitude of the differences in mechanical properties between the tensile bars. This indicated, again, that a knowledge of aging behavior in terms of microstructural aspects could aid the understanding of mechanical property variations with variations in aging treatment.

A further consideration was that the button head tensile bars were heat treated in a large vacuum furnace, whereas the threaded tensile bars were heat treated in a small air atmosphere furnace. Both sets of samples were cooled within the furnaces after solution annealing, however due to the difference in heat flow characteristics between the furnaces this cooling was done at different rates. The effect of cooling rate subsequent to solution annealing was checked by testing several 0.160-inch-diameter threaded tensile bars solution annealed at 1500°F for 1 hour; cooled to room temperature in the air furnace, vacuum furnace, oil, or water; and aged at 850, 900, or 950°F for 3 hours. Oil and water quenches were used to show the extent of a cooling rate effect. The results, Table 7, show that for a given aging temperature there is no difference in mechanical properties due to differences in cooling rate after solution annealing. This is consistent with observations of cooling rate effects on other similarly processed cobalt-containing maraging steels.[7]

Emphasis was now turned to the non-typical fractures (not the expected cup-and-cone), Figure 6, and surface cracks observed in some of the 0.252-inch-diameter threaded tensile bars and two of the 0.160-inch-diameter threaded tensile bars used in the cooling rate study. A longitudinal section of an 0.252-inch-diameter threaded tensile specimen aged at 850°F for 3 hours was mounted in Bakelite and ground until an interior crack was observed. Then, this sample was broken out of the mount and a transverse cut was made near the end of the crack to obtain a smaller sample. After immersing it in liquid nitrogen for several minutes, it was cracked in half along the existing crack by a hammer blow. The fracture halves were observed uncoated in the SEM after ultrasonic cleaning in acetone. Inclusions are indicated by the white areas on the crack revealed by the hammer blow (Figure 7) and on the tensile fracture surface (Figure 8).* A higher magnification photograph (Figure 9) shows the inclusions to be an integral part of the steel.* Also, brittle fracture of the inclusions is observed. Quantitative chemical analysis by Teledyne Vasco revealed the major components of the inclusions to be calcium, silicon, and aluminum (in order of decreasing percentage).* It is evident that these inclusions are the cause of the low ductilities presented in Table 4.

*Private letter from Alan M. Bayer, Teledyne Vasco, Latrobe, PA, 1984.

7. Metals Handbook, 9th ed., v. 1, ASM, Metals Park, Ohio, 1978, p. 447-448.

Table 7. EFFECT OF COOLING RATE AFTER SOLUTION ANNEALING* ON THE LONGITUDINAL MECHANICAL PROPERTIES (0.160-INCH-DIAMETER THREADED TENSILE SPECIMENS) OF VASCOMAX T-250

Aging Temperature, °F	Solution Annealing Furnace	Yield Strength, Ksi	Tensile Strength, Ksi	Reduction of Area, %	Elongation % in 1/2 in.
850	Air	228	240	58.7	13.2
		235	241	59.8	--
		232	241	59.3	13.2
	Vacuum	231	244	53.8	--**
		233	246	54.2	13.0
		232	245	54.0	13.0
	Air, OQ†	233	246	48.8	9.4**
	Air, WQ‡	235	249	59.7	13.3
900	Air	243	255	62.1	15.1
		249	259	63.2	13.2
		246	257	62.7	14.2
	Vacuum	240	255	61.2	13.2
		246	257	62.3	13.8
		243	256	61.8	13.5
950	Air	239	248	61.0	11.5
		241	251	66.7	13.3
		240	250	63.9	12.4
	Vacuum	244	251	61.7	--
		243	255	61.2	12.2
		244	253	61.5	12.2

*Solution annealed 1500°F for 1 hour
†Oil quench after solution anneal
‡Water quench after solution anneal
**Specimen had non-typical fracture appearance

The composition of the inclusions is similar to that of the rammed ingot mold wall used by Teledyne Vasco for this heat of steel. Experience has shown the producer that their rammed walls are susceptible to wash (i.e., erosion during pouring) when used with steels of high pouring temperature such as VascoMax T-250. In all probability this accounts for the existence of the inclusions. It must be noted that shortly after the first heats of VascoMax T-250 were melted, Teledyne Vasco recognized the problem and switched to brick ingot mold walls which minimize washing. It is therefore expected that such a problem no longer exists.*

Tensile Strength/Fracture Toughness Relationship

Figure 10 is a plot of tensile strength versus fracture toughness as a function of aging temperature and time. Numerous observations can be made. First, both the tensile strength and K_{IQ} increase as a function of aging temperture. Based on this trend the 950°F aging temperature gives maximum strength for this alloy in the investigated form (a 900°F aging temperature is used to achieve optimum properties in the 18% Ni 250 and 300 grade maraging steel). For example, a 900°F 4 hour treatment results in 255 ksi/96.7 ksi $\sqrt{in.}$ tensile strength-fracture toughness combination whereas the respective values for a 950°F 4 hour treatment are 256 ksi

*Personal discussion with Alan M. Bayer, Teledyne Vasco, Latrobe, PA, 1984.

and 106.6 ksi $\sqrt{in}$. In addition, as shown in Table 4, there is a very significant increase in impact energy, 22.6 to 28.7 ft-lb, when aging temperature is increased from 900 to 950°F.

A second point of interest is the range which was obtained in tensile strength for the 850°F 3 hour age as a function of specimen type and cooling rate. The biggest difference existed between the 0.252-inch-diameter button head and threaded type tensile specimens with values of 230 and 249 ksi, respectively. This difference is believed to be associated with the sensitivity of aging response to temperature for this underaged condition.

A final observation is the decrease in K_{IQ} for the 850°F aging temperature as a function of aging time. Although this is not necessarily unexpected with an increase in strength, the trend does differ from what is observed with the 900 and 950°F aging treatment. These differences are likely associated with aging response. For example, it has been shown that the mechanical properties of aged maraging steel are affected by thermomechanical processing treatments and aging time and temperature which determine levels of retained austenite and precipitate morphology.[8,9]

SUMMARY AND CONCLUSIONS

This report contains the results of a metallurgical characterization of VascoMax T-250 in 3-inch-diameter bar form. Hardness, tensile, toughness parameter data and microstructure are addressed as a function of aging temperature and time. Due to discrepancies which were observed in the tensile data and tensile fracture appearance this report also contains a detailed discussion relative to alloy heterogeneity. The conclusions from this program are as follows:

1. Tensile strength increases as a function of aging temperature (850, 900, and 950°F) and aging time (3, 4, and 8 hours).

2. Fracture toughness (K_{IQ}) increases as a function of aging temperature from 850 to 950°F, and Charpy energy is the highest for the 950°F aging conditions.

3. Based on (1) and (2) the 950°F age results in the maximum tensile strength and toughness properties for the material in the investigated form.

4. Discrepancies in the tensile data and tensile fracture appearance are attributed to the presence of exogenous inclusions which are believed to be associated with washing of the rammed ingot mold wall used for this heat.

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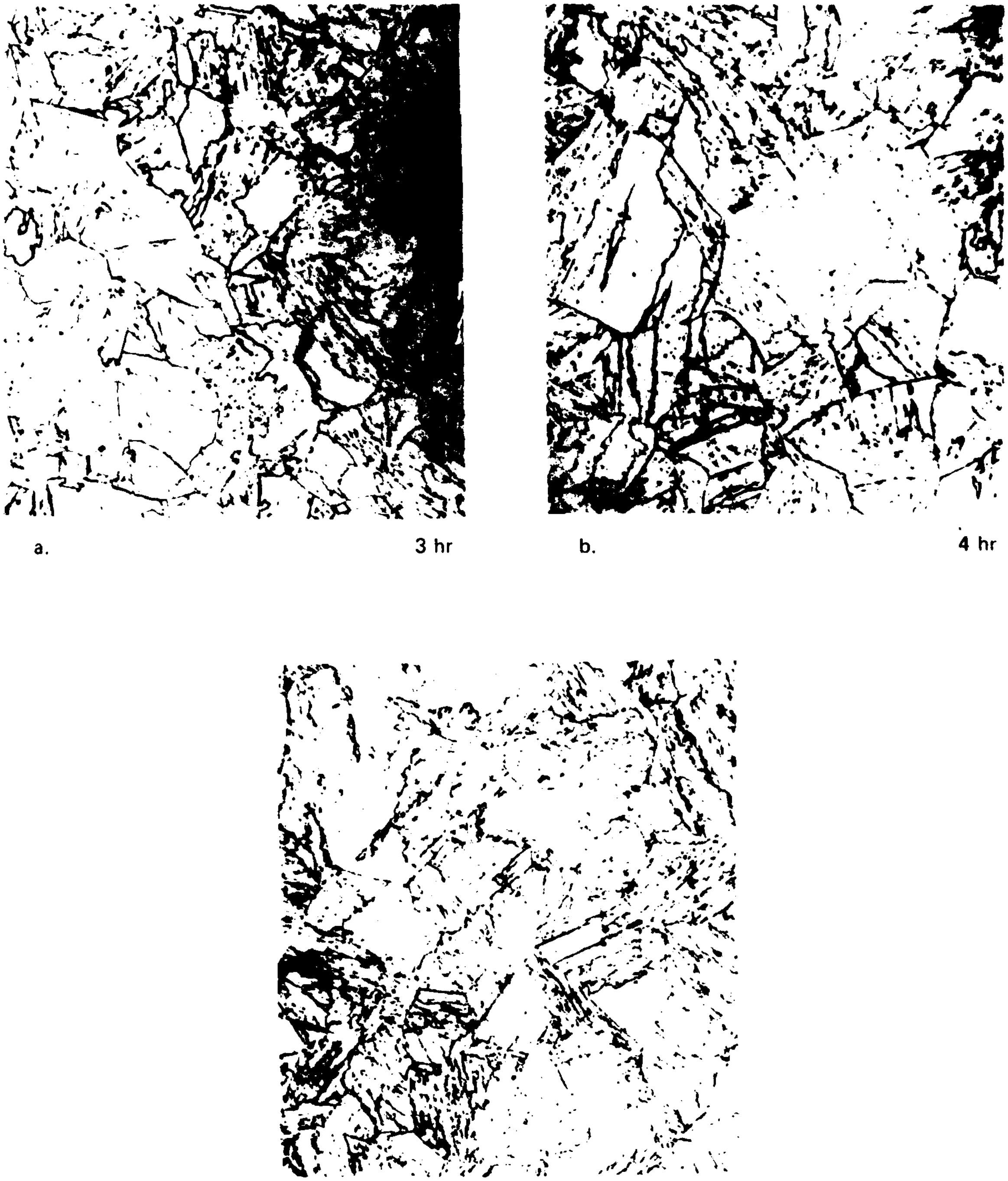
9. CARTER, C. S. *The Effect of Heat Treatment on the Fracture Toughness and Subcritical Crack Growth Characteristics of a 350 Grade Maraging Steel.* Metallurgical Transactions, v. 1, 1970, p. 1551-1559.



a. 3 hr

b. 4 hr

c. 8 hr

Figure 1. Microstructure from VascoMax T-250 Charpy impact specimens aged at 850°F as a function of aging time. Mag. 500X

Etchant: $FeCl_3$ in Ethanol with HCL Orientation: Longitudinal

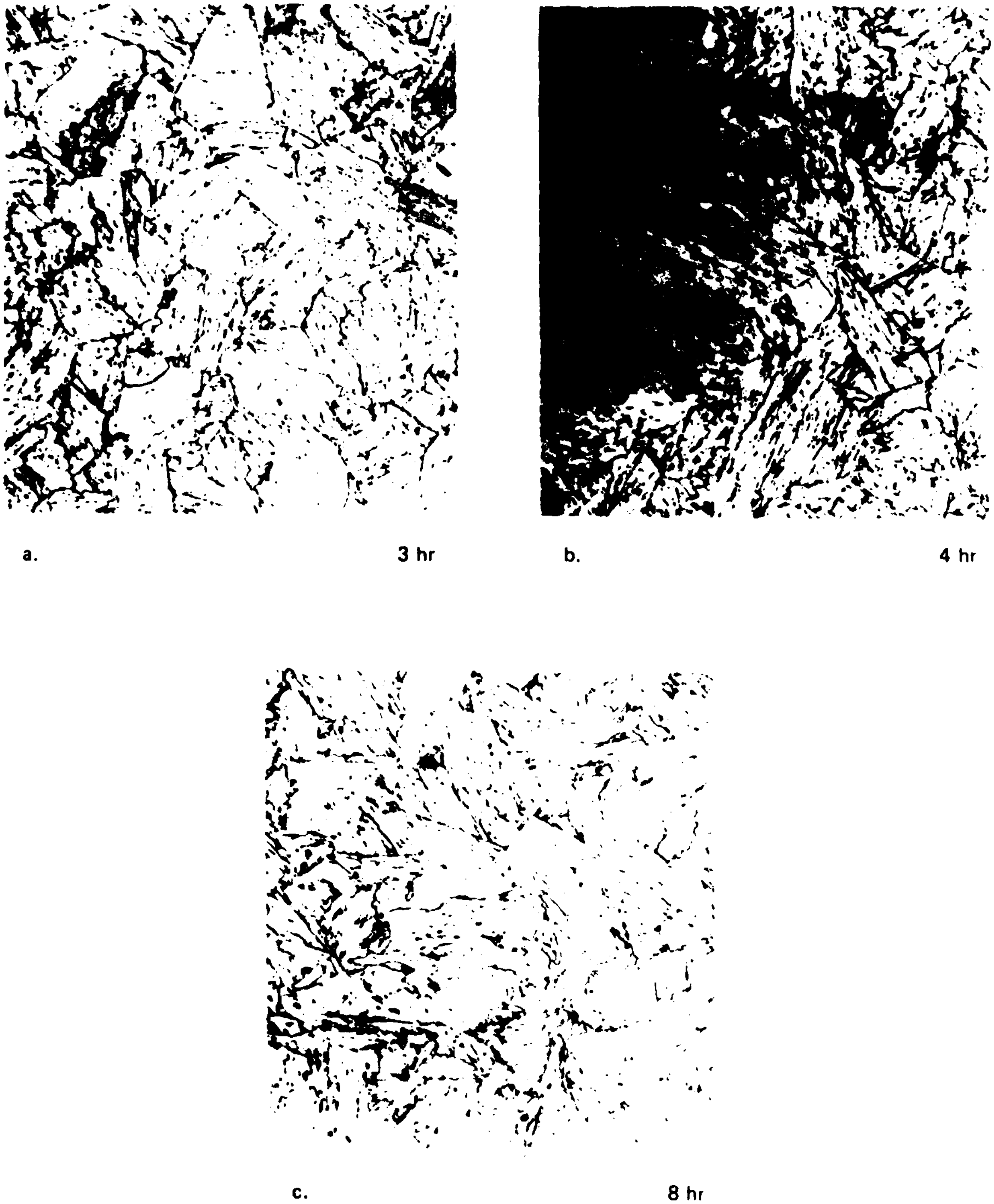
a. 3 hr

b. 4 hr

c. 8 hr

Figure 2. Microstructure from VascoMax T-250 Charpy impact specimens aged at 900°F as a function of aging time. Mag. 500X

Etchant: $FeCl_3$ in Ethanol with HCL Orientation: Longitudinal



a. 3 hr

b. 4 hr

c. 8 hr

Figure 3. Microstructure from VascoMax T-250 Charpy impact specimens aged at 950°F as a function of aging time. Mag. 500X

Etchant: $FeCl_3$ in Ethanol with HCL Orientation: Longitudinal

a. 850°F

b. 900°F

c. 950°F

Figure 4. Microstructure from VascoMax T-250 button-head tensile specimens aged for 3 hours as a function of aging temperature. Mag. 500X

Etchant: $FeCl_3$ in Ethanol with HCL

Orientation: (a) Transverse
(b) Longitudinal
(c) Longitudinal

a. 850°F

b. 900°F

c. 950°F

Figure 5. Microstructure from VascoMax T-250 threaded tensile specimens aged for 3 hours as a function of aging temperature. Mag. 500X

Etchant: $FeCl_3$ in Ethanol with HCL

Orientation: (a) Transverse
(b) Longitudinal
(c) Longitudinal

Figure 6. Nontypical fracture surface from a VascoMax T-250 threaded tensile specimen aged at 850°F for 3 hours. SEM Mag. 15X

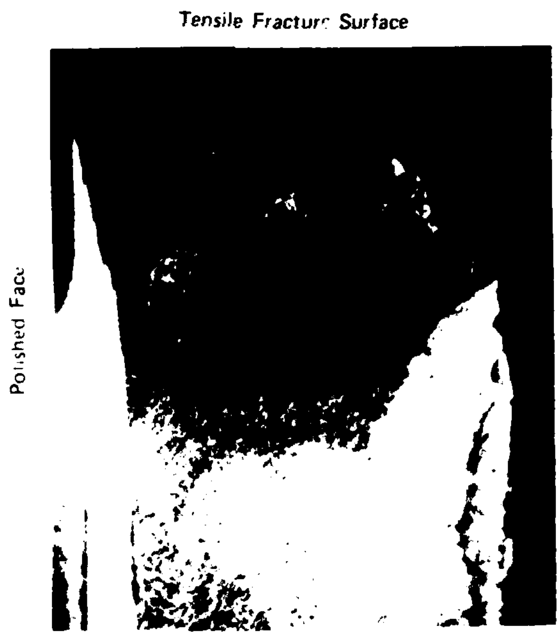


Figure 7. Crack within a VascoMax T-250 threaded tensile specimen aged at 850°F for 3 hours. This specimen exhibited low tensile ductility. SEM Mag. 20X

Figure 8. Inclusions on the tensile fracture surface of a VascoMax T-250 threaded tensile specimen aged at 850°F for 3 hours. Same specimen as in Figure 7. SEM Mag. 25X

Figure 9. Cracks at inclusion-metal interface within a VascoMax T-250 threaded tensile specimen aged at 850°F for 3 hours. Same specimen as in Figures 7 and 8. SEM Mag. 800X

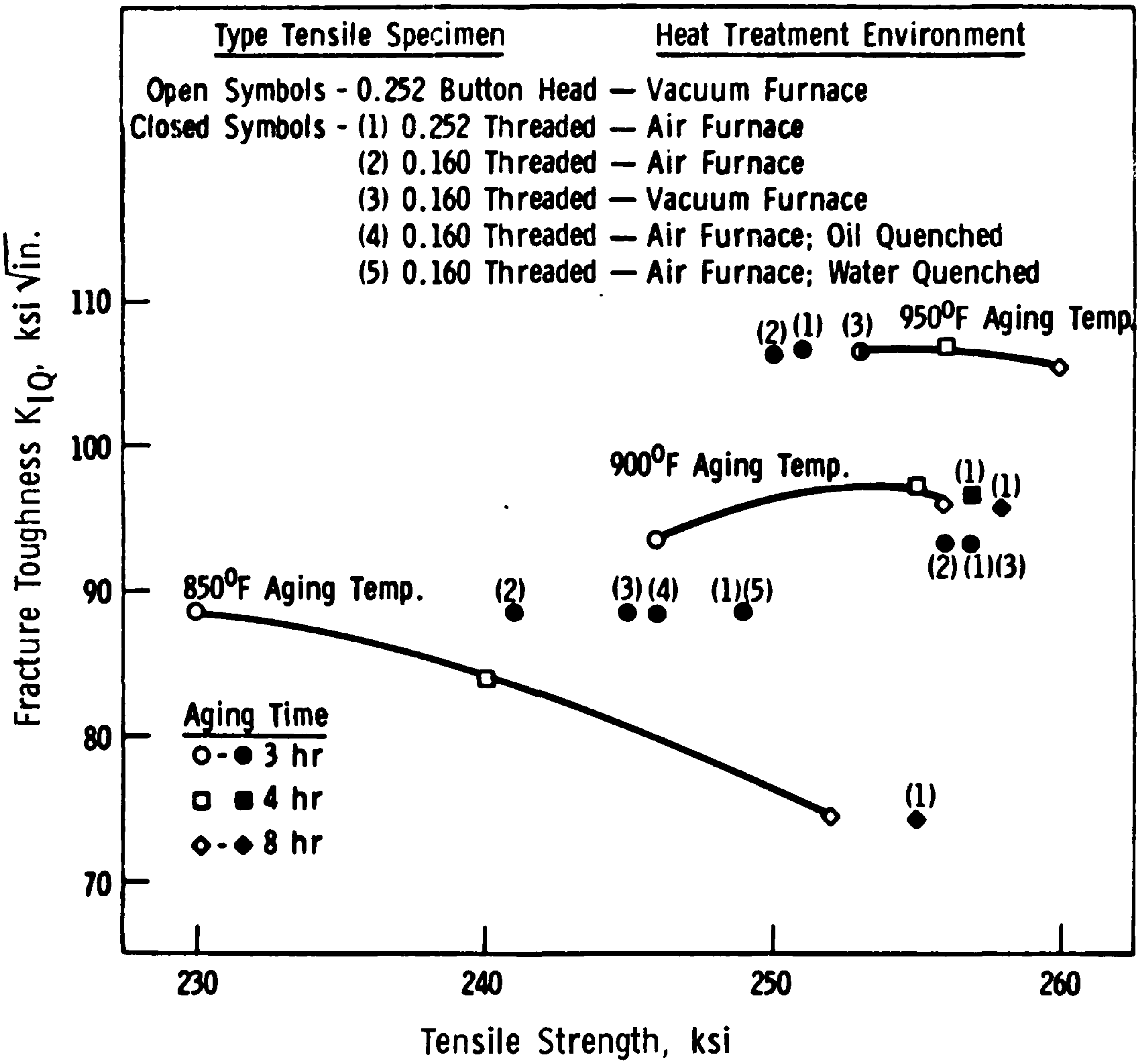


Figure 10. Tensile strength versus fracture toughness as a function of aging treatment.

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MECHANICAL PROPERTY CHARACTERIZATION OF VASCOMAX T-250 -
Charles F. Hickey, Jr., and Timothy S. Thomas

Technical Report MTL TR 86-30, August 1986, 21 pp - illus-tables, D/A Project: 1T161101A91A D081

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This report addresses a mechanical property characterization of VascoMax T-250 in the form of a 3-inch-diameter forged bar. Data were generated for aging temperatures of 350, 900, and 950°F and for aging times of 3, 4, and 8 hours. Parameters addressed were hardness, tensile properties, Charpy V-notch impact energy and fracture toughness. Microstructural aspects were also addressed. Results indicate that for the heat treatments investigated the tensile strength increases with increasing aging temperature and time. Fracture toughness (K_{IQ}) increases with aging temperature, and Charpy energy is the highest in the 950°F aged condition. Based on these findings the 950°F aging temperture results in the maximum tensile strength and toughness properties for the material in 3-inch-diameter bar form. Discrepancies in some of the tensile strength data and tensile fracture appearances are attributed to exogenous inclusions peculiar to this heat.

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