W. F. BROWN, JR.

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

1 **GENERAL**
AISI M50 is one of a class of semi-high-speed steels which have greater abrasion resistance than plain carbon steels but lower red hardness than the high-speed cutting steels. M50 is one of the leaner alloys of its class. High austenitizing temperatures are required to produce full hardness after tempering. The relatively low content of carbide phase results in rapid grain coarsening at the austenitizing temperature and for that reason close control of austenitizing temperature and time are required to produce a fine grain structure. The steel exhibits secondary hardening and is normally tempered near or at the peak of secondary hardness. Retained austenite can be reduced to negligible amounts by multiple tempering. The fully hardened steel is quite brittle and small cracks can result in catastrophic failure of components stressed well below the yield strength.
M50 is used in woodworking tools, hydraulic pump assemblies, pump pistons, pump vanes, in rolling element bearings operating at elevated temperatures, and in heavy duty gearing. M50 is widely used in aircraft gas turbine engine bearings and for this application high cleanliness and close composition control is obtained by vacuum induction melting (VIM) followed by consumable electrode melting (VAR). The low toughness of M50 is a limiting factor on the speed of large jet engine bearings and investigations are presently under way to produce bearings having races with a very hard surface but a relatively soft and tough core (28).

1.01 **Commercial Designation**
AISI M50, VASCO M-50, LATROBE MV-1, ALLEGHENY-LUDLUM HTB-2.

1.02 **Alternate Designations**
None

1.03 **Specifications**
1.031 AMS specifications, Table 1.031.
1.032 Inclusion ratings specified by AMS 6490 C and 6491, Table 1.032.

1.04 **Composition**
1.041 AMS composition limits, Table 1.041.

1.05 **Heat Treatment**
1.051 General. The general requirements for heat treating steels of this type are given in Reference 17 and the complex carbide changes during annealing, hardening, and tempering are discussed in detail in Reference 1. Relatively high austenitizing temperatures are necessary to ensure satisfactory carbide solution. Short exposure times at the austenitizing temperature are desirable in order to minimize grain size. Generally, hold times are no longer than to produce temperature equalization throughout the part (Table 1.058). Special attention should be given to avoid decarburization during annealing or austenitizing through the use of neutral salt baths or atmosphere furnaces. The steel exhibits secondary hardening in the tempering temperature range between 800 and 1100 F (Figure 1.0513). The as-quenched alloy contains substantial amounts of retained austenite (Figure 1.059) which is stable at tempering temperatures up to about 800 F. The transformation of the retained austenite occurs concurrently with the secondary hardening (Figure 1.059). The retained austenite content is well below 1 percent for tempering temperatures above about 1000 F for multiple tempered alloy. A cold treatment following the first of three tempers did not result in a decrease in the content of retained austenite (Figure 1.0510).

1.052 Normalizing. Not recommended (5).

1.053 Annealing. Heat slowly 1525 to 1650 F, 1 hr, FC at 35 F/hr maximum. Decarburization may be avoided by using controlled atmosphere or pack annealing with cast iron chips (5)(10). Hardness of the annealed condition is about 200 BHN (10).

1.054 Austenitizing. Preheat slowly 1500 to 1650 F. Harden at 2000 to 2050 F, only enough to equalize, preferably in neutral salt, AC or OQ. To minimize the possibility of cracking or distorting complex shapes, a salt quench at 1100 to 1150 F, 2 min., and AC from the hardening temperature is recommended (2)(6).

1.055 Cold treatment. To minimize retained austenite, a -100 F treatment immediately following quenching is recommended by one producer (4).

1.056 Tempering, 900 to 1200 F, AC. The maximum hardness will generally be obtained by tempering 1000 to 1025 F. Multiple tempers (cooling to room temperature between each temper) are generally used to minimize retained austenite. Triple tempering (2 + 2 + 2 hr) is sometimes used and there is evidence that the 2-hr temper repeated 5 times may increase the fracture toughness (see 3.0272). Multiple tempers have little effect on hardness (Figure 1.0513).

1.057 Stress relief. Stress relief following machining may be carried out at the tempering temperature.

1.058 AMS specified heat treatments, Table 1.058.

1.059 Effect of tempering temperature on retained austenite and hardness of CVM bar, Figure 1.059.

1.0510 Effect of tempering temperature on retained austenite in VIM + VAR bar, Figure 1.0510.

1.0511 Effect of austenitizing temperature on hardness and grain size of oil quenched or air cooled CVM bar, Figure 1.0511.

1.0512 Effect of tempering time on hardness of air induction melted bar, Figure 1.0512.

1.0513 Effect of multiple tempering on the hardness of CVM alloy, Figure 1.0513.

1.0514 The effect of tempering temperature on the hardness of VIM + VAR bar, Figure 1.0514.

1.0515 Effect of tempering temperature on the hardness of VIM + VAR bar austenitized at several temperatures, Figure 1.0515.

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

1.06 Hardness

1.061 General. A high initial hardness following tempering and the stability of this hardness for long times at elevated temperatures are necessary to minimize spalling and pitting of bearings during service. A minimum hardness of 58 R_C has been suggested for critical bearing applications such as would be encountered in gas turbines (18)(19). The steel is deep hardening and hardness levels of 60 to 64 R_C should be obtainable at the center of 4-inch thick sections. The available hardness data support the conclusion that for steel having a room temperature hardness greater than 60 R_C the hardness at 600 F will be greater than 58 R_C. The stability of the initial as heat treated room temperature hardness to long time exposure at elevated temperature depends on the initial hardness level (Figure 1.064). Data concerning the effects of exposure at the test temperature to the hardness at this temperature (Figure 1.065) indicate that 1000 hr exposure to 600 F will reduce the 600 F hardness from 59 R_C to about 57 R_C for a steel with an initial as heat treated hardness of 64 R_C. According to Figure 1.066 the steel with an initial room temperature hardness of about 62 R_C had an 800 F hardness of about 58 R_C after 750 hr exposure at 800 F. Stability effects would be expected to depend on both the initial hardness and the composition limits with the higher hardness levels being somewhat less stable after exposure at elevated temperatures for extended times.

1.062 Effect of test temperature on the hardness of CVM bar, Figure 1.062.

1.063 Effect of test temperature on the hardness of CVM forging tempered at 950 or 1075 F, Figure 1.063.

1.064 Stability temperature of room temperature hardness for various exposure times, Figure 1.064.

1.065 Effect of exposure temperature and test temperature on hardness of air induction melted bar, Figure 1.065.

1.066 Effect of exposure to 600 and 800 F for various times on hardness at the exposure temperature and at room temperature after long exposure, Figure 1.066.

1.067 Effect of test temperature on Vickers hardness of CVM alloy, Figure 1.067.

1.068 Effect of high test temperature on hardness of VIM-VAR bar, Figure 1.068.

1.069 Effect of test temperature on hardness of CVM bar, Figure 1.069.

1.07 Forms and Conditions Available

1.071 Bars, forgings, and tubing in as formed or annealed condition.

1.08 Melting and Casting Practice

1.081 Applications in high-speed bearings and in gearing require material of closely controlled composition, low content of tramp elements, and generally high cleanliness. Consumable electrode melting (CVM) or vacuum induction melting followed by consumable electrode melting (VIM-VAR) is necessary to meet these requirements. The preferred method for highest quality is VIM-VAR (Table 1.082). The details of this melting practice are discussed in References 7 and 16, with particular reference to improved aircraft bearing performance.

1.082 Gas content and inclusion ratings for various melting practices, Table 1.082.

1.09 Special Considerations

1.091 Cleanliness and microstructure must be closely controlled for critical bearing applications. Double vacuum melting (VIM-VAR) coupled with careful control of the heat treatment are necessary to achieve low inclusion content, a small grain size, and uniform carbide distribution (see 1.05 and 1.08).

1.092 Like other tool steels, the high hardness conditions of this alloy have low fracture toughness and this has become a cause for concern as the speed of the large bore rolling element bearings has increased. The combination of the large bore and the high speed results in high centrifugal stresses which can cause catastrophic race failure in the presence of small cracks originating from spalls (see 3.0272).

1.093 Dimensional change following 1000 hr exposure to elevated temperatures, Table 1.093.

2 PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range.

2.012 Phase changes, A_c 1490 to 1555 F, A_r 1385 to 1345 F.

2.0121 Time-temperature-transformation diagrams.

2.01211 Isothermal transformation diagram, Figure 2.01211.

2.013 Thermal conductivity.

2.0131 Thermal conductivity of CVM forging, Table 2.0131.

2.014 Thermal expansion.

2.0141 Coefficient of thermal expansion, Figure 2.0141.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.288 lb per cu in. [7.97 gm per cc] (12).

2.022 Electrical properties.

2.023 Magnetic properties. Alloy is ferromagnetic.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Environment

2.031 General. The alloy is subject to oxidation in normal air if not protected. From experience with other tempered martensitic steels it might be expected that crack propagation would be influenced by the service environment. However, no information on such effects was available at the time this chapter was prepared.

2.032 Oxidation of CVM alloy exposed in air for 50 and 150 hr at the tempering temperature, Table 2.032.

2.04 Nuclear Environment

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

3 **MECHANICAL PROPERTIES**

3.01 **Specified Mechanical Properties**

3.011 AMS specified mechanical properties, Table 3.011.

3.02 **Mechanical Properties at Room Temperature**

3.021 Tension properties. Tension – Stress/strain diagrams.

3.0211 Effect of tempering temperature on the tensile properties of VIM-VAR bar, Figure 3.0211.

3.022 Compression properties. Compression – Stress/strain diagrams (see 3.032).

3.023 Impact.

3.0231 Effect of tempering temperature on the unnotched Izod impact energy of CVM bar austenized at 2000 or 2050 F, Figure 3.0231.

3.0232 Effect of tempering temperature on the unnotched Izod impact energy of VIM-VAR bar austenitized at several temperatures, Figure 3.0232.

3.024 Bending.

3.025 Torsion and shear.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties.

3.0272 Fracture toughness.

3.02721 General. When this steel is heat treated to the high hardness levels used in high-speed bearings and in gearing, it exhibits low plane strain fracture toughness. Tempering at temperatures beyond those corresponding to the secondary hardening peak results in rising fracture toughness with only small losses in tensile strength hardness (compare Figure 3.02722 with Figures 3.0211 and 1.0514). However, data are insufficient to define the extent of increased toughness and decreased strength and hardness associated with overtempering. It has recently been reported that the plane strain fracture toughness of the same material as represented by the data in Figure 3.02722 can be increased to 21 ksi-$\sqrt{\text{in.}}$ by tempering five times at 1000 F (20). This multiple tempering cycle did not change the hardness and would not be expected to change the tensile strength.

3.02722 Effect of tempering temperature on the plane strain fracture toughness of bar, Figure 3.02722.

3.028 Combined properties.

3.03 **Mechanical Properties at Various Temperatures**

3.031 Tension properties. Tension – Stress/strain diagrams.

3.0311 Effect of elevated temperatures on the tensile properties of CVM bar, Figure 3.0311.

3.032 Compression properties. Compression – Stress/strain diagrams.

3.0321 Effect of test temperature on compression yield strength of air induction melted bar, Figure 3.0321.

3.033 Impact.

3.034 Bending.

3.035 Torsion and shear.

3.036 Bearing.

3.037 Stress concentration.

3.0371 Notch properties.

3.0372 Fracture and fracture toughness.

3.038 Combined properties.

3.04 **Creep and Creep-Rupture Properties**

3.05 **Fatigue Properties**

3.051 General. There is considerable information on the performance of this steel under conditions representing service in high-speed bearings (22)(23)(25)(26). M50 steel is considerably superior to SAE 52100 for bearing applications above about 350 F. It has been further demonstrated that VIM-VAR melting of M50 increases bearing life compared to air plus VAR melting (Table 3.052).

3.052 Comparative performance of AM + VAR and VIM + VAR material in a rolling contact fatigue test, Table 3.052.

3.053 S-N curves for VIM bar at room temperature and 500 F, Figure 3.053.

3.054 Crack propagation rate as a function of stress intensity factor range for VIM-VAR bar, Figure 3.054.

3.06 **Elastic Properties**

3.061 Poisson's ratio.

3.062 Modulus of elasticity.

3.0621 Effect of test temperature on modulus of elasticity, Figure 3.0621.

3.063 Modulus of rigidity, 12,000 ksi (11).

3.064 Tangent modulus.

3.065 Secant modulus.

4 **FABRICATION**

4.01 **Forming**

4.011 Forging. Preheat 1400 to 1500 F to equalize and then heat to a maximum forging temperature of 2050 F (4)(6)(10)(11). Minimum forging temperature is given as 1800 F (4), 1700 F (6) (11), and 1600 F(10). Forgings should be furnaced cooled or very slowly cooled in an insulating material.

4.012 Ausforging. Ausforging of this steel may be carried out between about 850 and 1100 F. This process is particularly effective in producing a structure with small and uniformly distributed carbides. Studies conducted in bearing test rigs, actual bearing tests, and in gear tests indicate superior performance for ausforged CVM material as compared with that conventionally forged (21)(22)(23)(27). However, large reductions [80 percent] are necessary to obtain substantial improvements and it becomes increasingly difficult and costly to produce sound forgings as the size increases. Because of these difficulties and because the advent of VIM-VAR melting has substantially increased performance, ausforging has not gained commercial acceptance.

4.013 Effect of high test temperature on tensile impact energy of VIM-VAR as-forged billet, Figure 4.013.

4.02 **Machining and Grinding**

4.021 General. The machinability is rated between 55 and 65 percent of a 1 percent carbon water

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

hardening tool steel, or about 45 to 55 percent of AISI B1112. Approximate turning speeds of 70 to 90 surface feet per minute are recommended when using high speed cutting tools (5)(6).

4.03 **Joining**

4.031 Welding or brazing is not recommended (12).

4.04 **Surface Treating**

REFERENCES

1 Bridge, J. Edwin, Jr., Maniak, G. N., and Philip, T. V., "Carbides in M-50 High Speed Steel", Met. Trans. Vol. 2 (August 1971) p 2209.

2 AMS 6490 C (December 15, 1974).

3 AMS 6491 (January 15, 1976).

4 Berger, E. J., Carpenter Technology Corp., Technical Data on M-50 Steel (June 4, 1981).

5 Bhat, G. K. and Nehrenberg, A. E., "A Study of the Metallurgical Properties of Bearing Materials at Temperatures in the Range from Room Temperature to 1000 F for Aircraft Service", Crucible Steel Corp. AFML Contract AF 33(616)-3318 WADC Report 57-343 (April 1957).

6 Latrobe Steel Corp. Data Sheet, Lescalloy M50 VIM-VAR (June 1977).

7 Schlatter, R. and Stroup, J. P., "Improved M-50 Aircraft Bearing Steel Through Advanced Vacuum Melting Processes", J. Vac. Sci. Tech. Vol. 9 No. 6 (December 1972) p 1326.

8 Latrobe Steel Co., "Metallurgical Report Hot Hardness Characteristics of Speciality Bearing Steels" (July 1965).

9 High Temperature High Strength Alloys, Am. Iron and Steel Institute (February 1968).

10 Allegheny-Ludlum Steel Corp., Pittsburgh, PA M-50 Data Sheets.

11 Vanadium Alloys Steel Co., Vasco M-50 Data Sheets (1974).

12 General Electric, Materials Handbook, Section 2 Iron Base Alloy M-50 (September 12, 1973).

13 Rescalvo, J. A. and Auerbach, B. L., "Fracture & Fatigue in M-50 & 18-4-1 High Speed Steels", Met. Trans. Vol. 10A (September 1979) p 1265.

14 Chevalier, J. I., Dietrich, M. W., and Zaretsky, E. V., "Hot Hardness Characteristics of Ausformed AISI M-50, Matrix II, WD-65, Modified 440C and Super Nitralloy", NASA TN D 7244 (May 1973).

15 Latrobe Steel Corp. Electrite MV-1 (1964).

16 Schlatter, R., "Double Vacuum Melting of High Performance Bearing Steels", Industrial Heating (September 1974) p 40.

17 Roberts, G. A., Hamaker, J. C., and Johnson, A. R., Tool Steels, 3rd Edition, ASM (1962).

18 Bamberger, E. N. and Harris, T., "Life Adjustment Factors for Ball and Roller Bearings – An Engineering Design Guide", ASME New York, NY (1971).

19 Schlict, H. and Zwirlein, O., "Varying Heat Treatment Parameters to Optimize Material and Roller Contact Fatigue Strength", Journal of Heat Treating, Vol. No. 3 (June 1980) p 73.

20 Private communication with E. N. Bamberger, General Electric Aircraft Engine Group. Project Manager on AF Contract 33615-80-C-2018 reporting data obtained by B. L. Auerbach on this contract (1982).

21 Bamberger, E. N., "The Effect of Ausforming on the Rolling Contact Fatigue Life of a Typical Bearing Steel", Journal of Lubrication Technology, Trans. ASME (January 1967) p 63.

22 Bamberger, E. N., "Materials for Rolling Element Bearings", Bearing Design – Historical Aspects, Present Technology, and Future Problems, International Conference on Bearing Design, W. J. Anderson, Editor ASME (August 1980).

23 Parker, R. J. and Zaretsky, E. V., "Rolling-Element Fatigue Life of Ausformed M-50 Steel Balls", NASA TN D 4954 (December 1968).

24 Bamberger, E. N., "Thermomechanical Working of Electroslag Melted M 50 Bearing Steel", General Electric Co. AF33615-70-C-1234, AFML TR 72-183 (July 1972).

25 Morrison, F. R., McCool, J. I., and Ninos, N. J., "M 50 Steel Bearing Material Factors for Rolling Element Life Calculations", SKF Technology Services, AVRADCOM Technical Report TR 79-35 (April 1979).

26 Parker, R. J. and Zaretsky, E. V., "Rolling Element Fatigue Bearing Life of AISI M-50 18-4-1 Balls", NASA Technical Paper 1202 (April 1978).

27 Townsend, D. P., Bamberger, E. N., and Zaretsky, E. V., "A Life Study of Ausforged, Standard Forged and Standard Machined AISI M-50 Spur Gears", Journal of Lubrication Technology, Trans. ASME (July 1976) p 418.

28 AF Contract 33615-80-C-2018, General Electric Aircraft Engine Group, E. N. Bamberger, Manager.

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V	
AMS	Form	Condition
6491	Bars, Forgings, and Tubing	Consumable Vacuum Melt
6490 C	Bars, Forgings, and Tubing	Double Vacuum Melt (VIM-VAR)

TABLE 1.031. AMS SPECIFICATIONS

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V							
Form	Bars, Forgings, and Tubing							
Source	AMS 6490 C(a)				AMS 6491(b)			
Condition	CVM				VIM + VAR			
Inclusion Type(c)(d) Worst Field	A	B	C	D	A	B	C	D
Thin	2.0	1.5	1.5	1.5	1.5	1.0	1.0	1.5
Heavy	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

(a) Radial specimens 0.28 $in.^2$ surface area, fully heat treated, and examined on face parallel to rolling direction.

(b) Radial specimens 0.28 $in.^2$ surface area taken midway between center and surface of hardened fracture samples (>55 R_C), examined on face parallel to rolling direction.

(c) Rating by ASTM E45 method D Plate III.

(d) A – Sulphides, B – Alumina, C – Silicates, and D – Globular Oxides.

TABLE 1.032. INCLUSION RATINGS SPECIFIED BY AMS 6490 C AND 6491

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V			
Form	Bars, Forgings, and Tubing			
Source	AMS 6491 (3)		AMS 6490 C (2)	
	Percent		Percent	
Composition	Min	Max	Min	Max
C	0.80	0.85	0.77	0.85
Mn	0.15	0.35	–	0.35
Si	–	0.25	–	0.25
P	–	0.015	–	0.015
S	–	0.008	–	0.015
Cr	4.00	4.25	3.75	4.25
Mo	4.00	4.50	4.00	4.50
V	0.90	1.10	0.90	1.10
Ni	–	0.15	–	0.15
Co	–	0.25	–	0.25
W	–	0.25	–	0.25
Cu	–	0.10	–	0.10

TABLE 1.041. AMS COMPOSITION LIMITS

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V	
Form	Bars, Forgings, and Tubing	
Source	AMS 6490 C	AMS 6491
Condition	CVM	VIM-VAR
Preheat	1500 - 1600 F	–
Austenitize	2025 - 2050 F	2025 - 2050 F
Time	To Equalize	To Equalize
Salt Quench	1100 - 1150 F	1100 - 1150 F(a)
Time	> 2 min, AC	108 to 132 sec
Temper	1000 - 1025 F 2 hr AC	1000 - 1025 F 1.75 to 2.25 hr AC
Hardness R_C	60-64	60 (Min)

(a) This step may be omitted and austenitized specimens may be air cooled before tempering.

TABLE 1.058. AMS SPECIFIED HEAT TREATMENTS

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

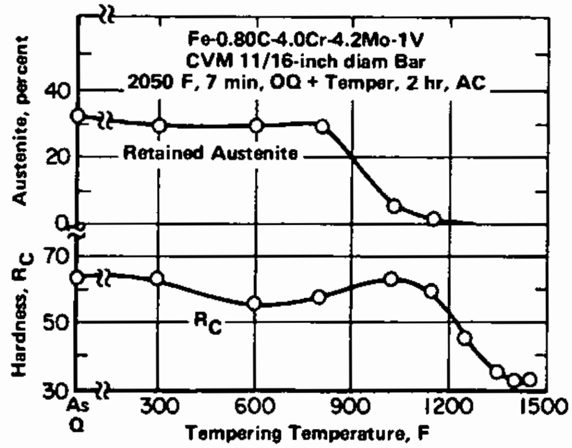

FIGURE 1.059. EFFECT OF TEMPERING TEMPERATURE ON RETAINED AUSTENITE AND HARDNESS OF CVM BAR (1, FIGURE 2)

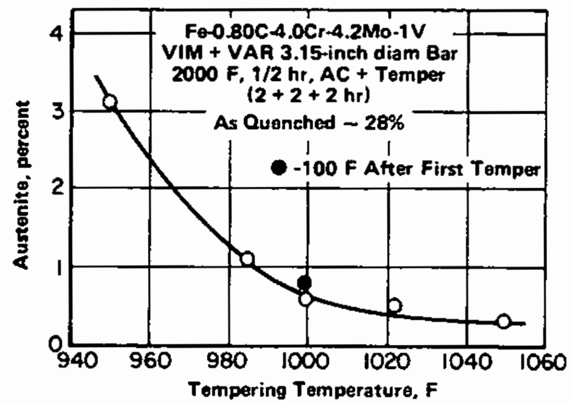

FIGURE 1.0510. EFFECT OF TEMPERING TEMPERATURE ON RETAINED AUSTENITE IN VIM + VAR BAR (13, TABLE 5)

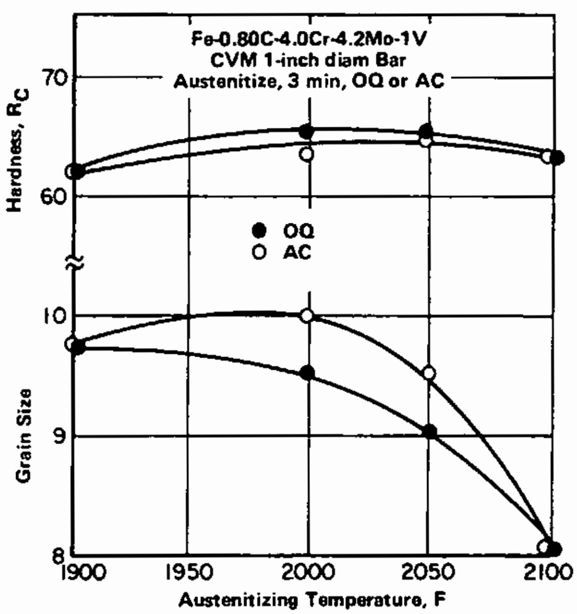

FIGURE 1.0511. EFFECT OF AUSTENITIZING TEMPERATURE ON HARDNESS AND GRAIN SIZE OF OIL QUENCHED OR AIR COOLED CVM BAR (10)

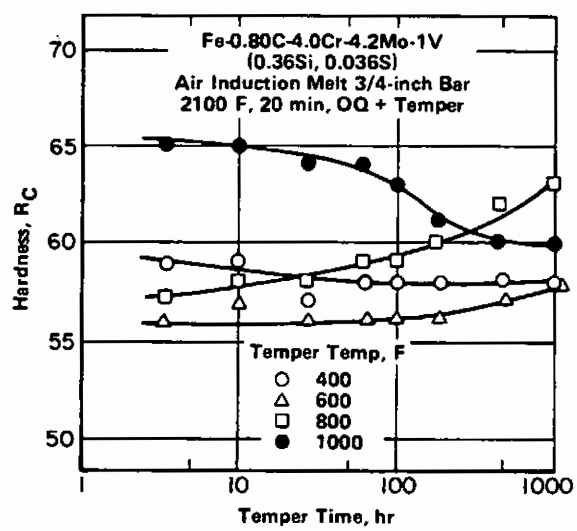

FIGURE 1.0512. EFFECT OF TEMPERING TIME ON HARDNESS OF AIR INDUCTION MELTED BAR (5, TABLE 3)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

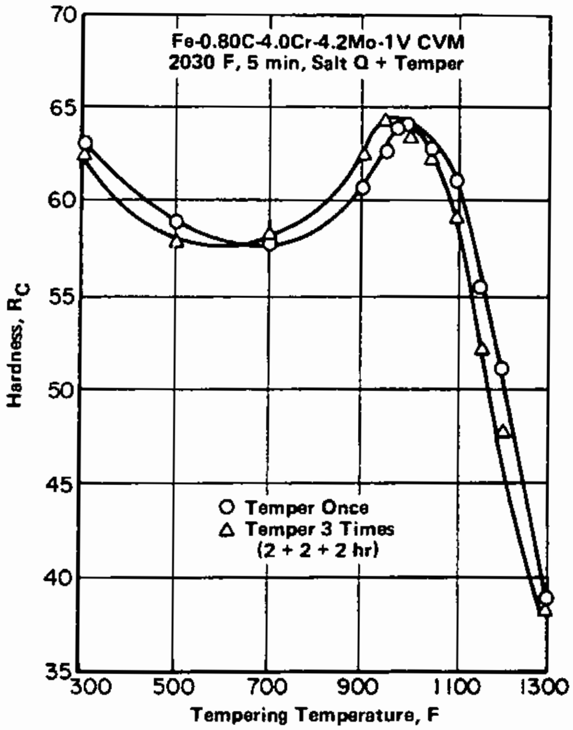

FIGURE 1.0513. EFFECT OF MULTIPLE TEMPERING ON THE HARDNESS OF CVM ALLOY (11)

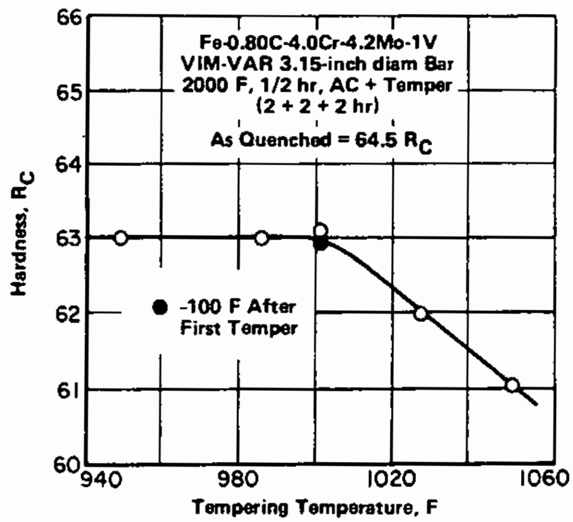

FIGURE 1.0514. EFFECT OF TEMPERING TEMPERATURE ON THE HARDNESS OF VIM-VAR BAR (13, FIGURE 1)

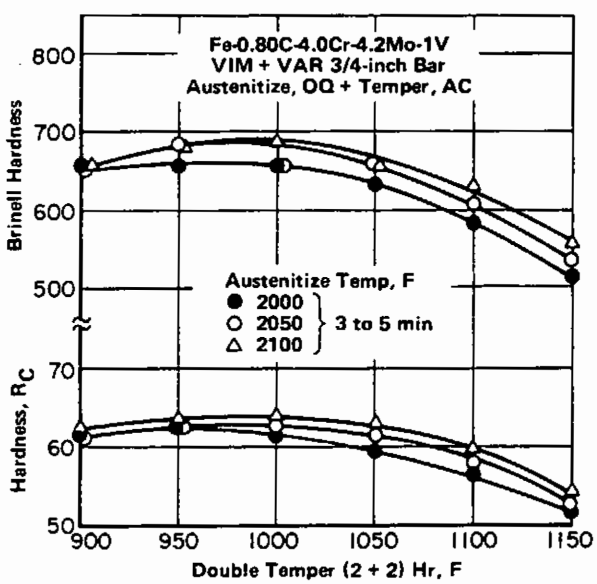

FIGURE 1.0515. EFFECT OF TEMPERING TEMPERATURE ON THE HARDNESS OF VIM + VAR BAR AUSTENITIZED AT SEVERAL TEMPERATURES (4)

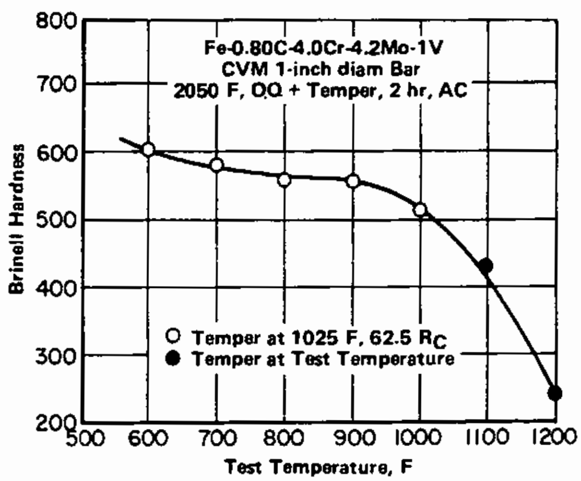

FIGURE 1.062. EFFECT OF TEST TEMPERATURE ON THE HARDNESS OF CVM BAR (10)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

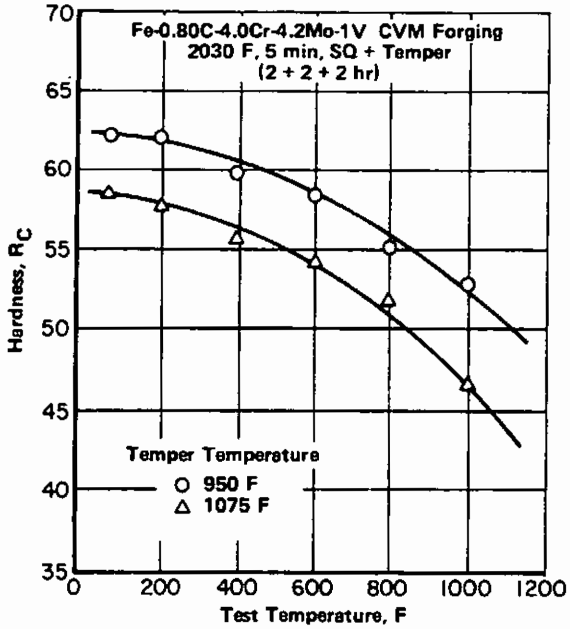

FIGURE 1.063. EFFECT OF TEST TEMPERATURE ON HARDNESS OF CVM FORGING TEMPERED AT 950 OR 1075 F (11)

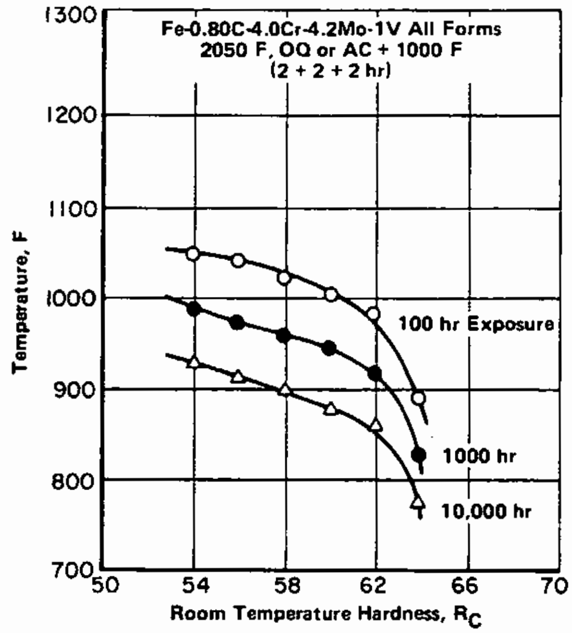

FIGURE 1.064. STABILITY TEMPERATURE OF ROOM TEMPERATURE HARDNESS FOR VARIOUS EXPOSURE TIMES (11)

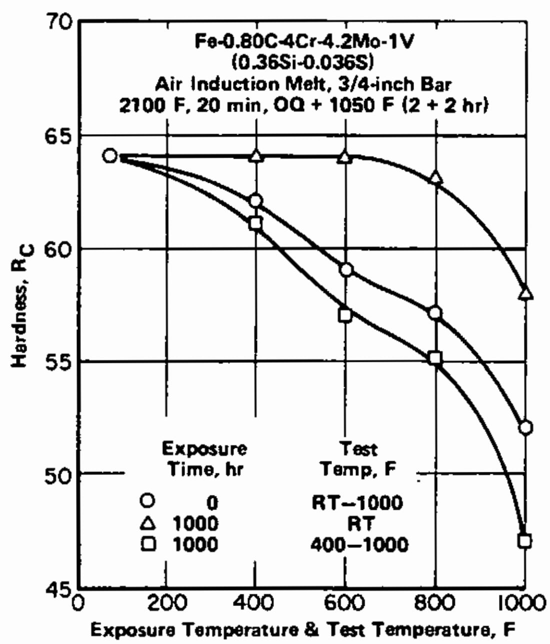

FIGURE 1.065. EFFECT OF EXPOSURE TEMPERATURE AND TEST TEMPERATURE ON HARDNESS OF AIR INDUCTION MELTED BAR (5, TABLE 4)

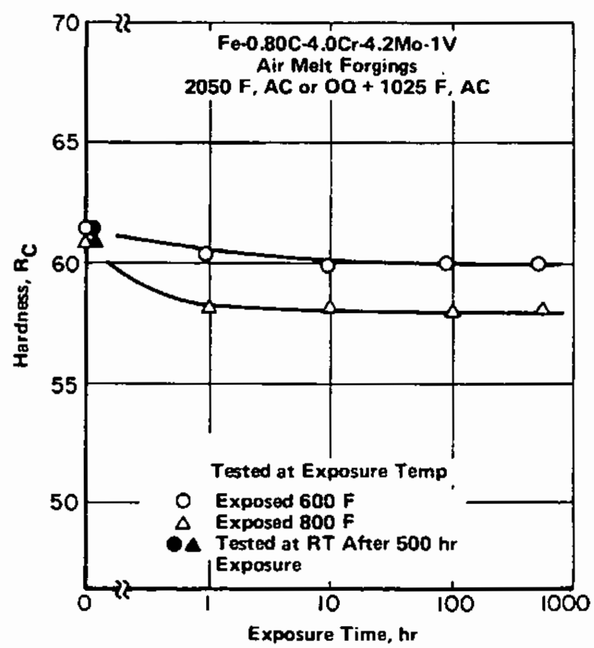

FIGURE 1.066. EFFECT OF EXPOSURE TO 600 AND 800 F FOR VARIOUS TIMES ON HARDNESS AT THE EXPOSURE TEMPERATURE AND AT ROOM TEMPERATURE AFTER LONG EXPOSURE (8, TABLES 2 AND 3)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

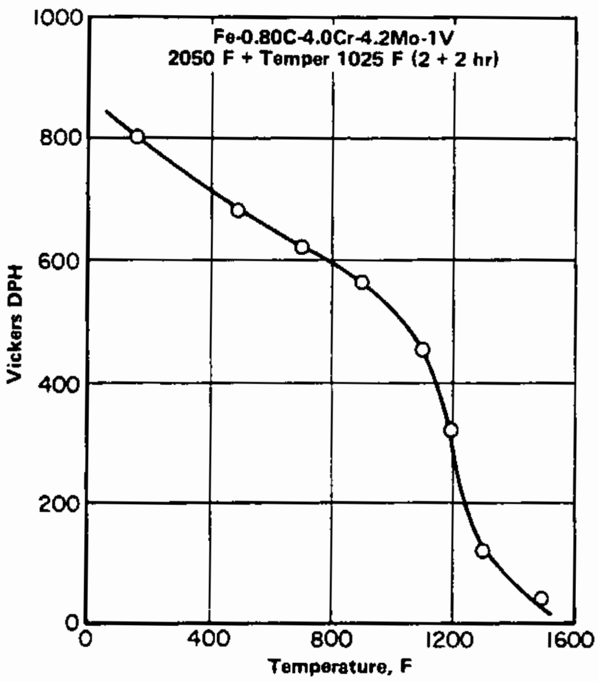

FIGURE 1.067. EFFECT OF TEST TEMPERATURE ON VICKERS HARDNESS OF CVM ALLOY (11)

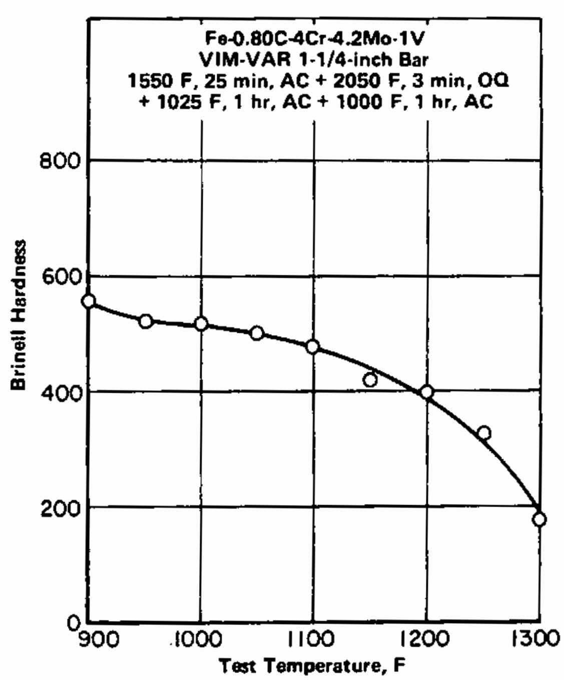

FIGURE 1.068. EFFECT OF HIGH TEST TEMPERATURE ON HARDNESS OF VIM-VAR BAR (4, FIGURE 1)

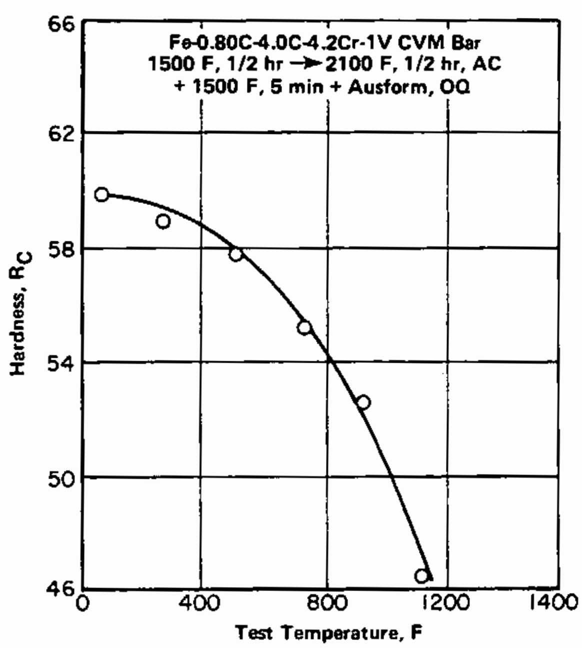

FIGURE 1.069. EFFECT OF TEST TEMPERATURE ON HARDNESS OF CVM BAR (14, FIGURE 3)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V						
Form	0.4-inch diam Bar						
Condition	1550 F, 6 min → 2050 F (Salt), 3 min, Salt Q, 1050 F, AC + 1050 F (2 + 2 hr), AC + 1050 - 1070 F, AC to give 61.5 to 62 R_C						
Melt[(a)] Practice	AM	AM + VG	AM + VAR	AM + 2 VAR	AM + 3 VAR	VIM	VIM + VAR
Gas Content, ppm							
H_2	4.8	3.2	1.8	<1.0	<1.0	<1.0	<1.0
N_2	150	120	80	60	50	85	60
O_2	67	46	37	9	5	21	6
Inclusion Rating[(b)]							
Worst Field							
A Thin	–	–	1/2	–	–	–	1/2
A Heavy	–	–	0	–	–	–	0
B Thin	–	–	1/2-1	–	–	–	1/2-1
B Heavy	–	–	0	–	–	–	0
C Thin	–	–	0	–	–	–	0
C Heavy	–	–	0	–	–	–	0
D Thin	–	–	1	–	–	–	1
D Heavy	–	–	0	–	–	–	0

(a) AM – Air Melt, VG – Vacuum Degass, VAR – Consumable Vacuum Arc Remelt, and VIM – Vacuum Induction Melt.
(b) Rating by ASTM E145 (100X).

TABLE 1.082. GAS CONTENT AND INCLUSION RATINGS FOR VARIOUS MELTING PRACTICES (7p, 1329)

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V (0.036S-0.365Si)
Form	Air Induction Melt, 3/8-inch Bar
Condition	2100 F, 20 min, OQ + 1050 F (2 +2 hr), AC
1000 hr Exposure Temp, F	Length Change, percent[(a)]
400	0.0022
600	0.0012
800	0.0027
1000	0.0050

(a) Specimen 4.000±0.001-inch long. Estimated precision of measurement 0.001 percent.

TABLE 1.093. DIMENSIONAL CHANGE FOLLOWING 1000 HR EXPOSURE TO ELEVATED TEMPERATURES (5, TABLE 5)

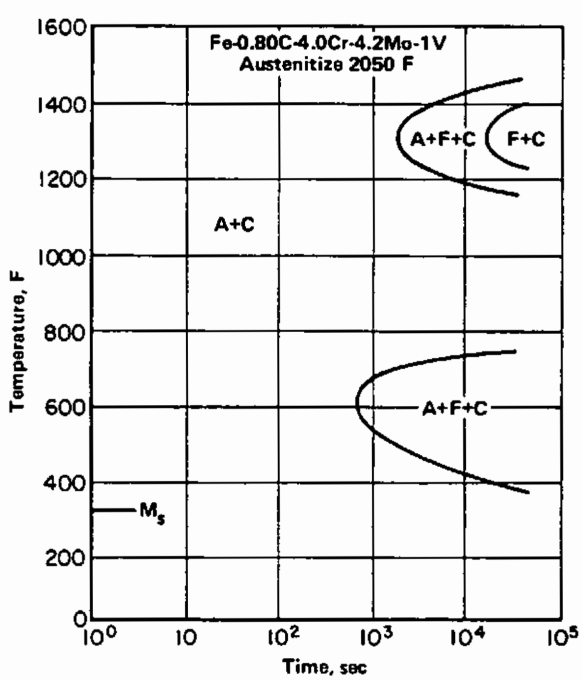

FIGURE 2.01211. ISOTHERMAL TRANSFORMATION DIAGRAM (4)

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V		
Form	CVM Forging		
Condition	Annealed or Heat Treated		
Temp, F	212	572	932
Thermal Conductivity, Btu ft/(hr ft^2 F)	21.4	20.2	19.7

TABLE 2.0131. THERMAL CONDUCTIVITY OF CVM FORGING (15)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

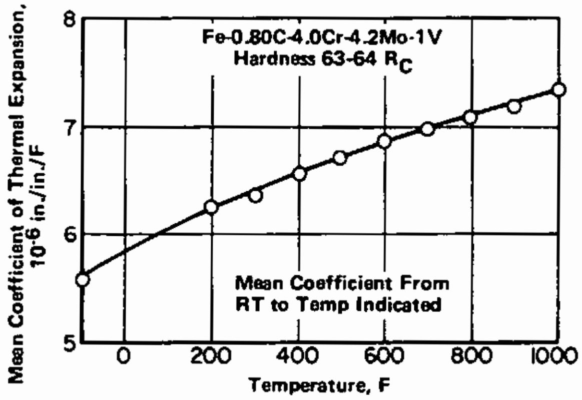

FIGURE 2.0141. COEFFICIENT OF THERMAL EXPANSION (6, 15)

Alloy	Fe-0.80C-4.0Cr-42.Mo-1V			
Form	CVM 1/4-inch Thick			
Condition	1500 F → 2050 F, OQ + Temper 2 hr			
Exposure Time in Air	50 hr		150 hr	
Temper Temp, F	1000	1100	1000	1100
Exposure Temp, F	1000	1100	1000	1100
Weight Gain, mg/cm2	0.281	1.81	0.481	2.36

TABLE 2.032. OXIDATION OF CVM ALLOY EXPOSED IN AIR FOR 50 AND 150 HR AT THE TEMPERING TEMPERATURE (10)

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V				
AMS	6491 and 6490 C				
Form	Bars Diam ≤ 0.500 inch	Bars Diam > 0.500 inch		Mechanical Tubing	
Condition(a)	Cold Finish(b)	Hot Finish	Cold Finish	Cold Finish	Hot Finish
F_{tu}, ksi (Min)	120(c)	–	–	–	–
Hardness, BHN (Min)	–	229(b)	248(b)	–	–
Hardness, R_C or RB (Min)	–	–	–	25 R_C	99 R_B

(a) Fully heat treated: AMS 6491 gives 60 R_C (minimum), AMS 6490 C gives 60 to 64 R_C.
(b) AMS 6490 C specifies sphereodize anneal following hot or cold finish.
(c) AMS 6490 C gives 125 ksi (maximum).

TABLE 3.011. AMS SPECIFIED MECHANICAL PROPERTIES

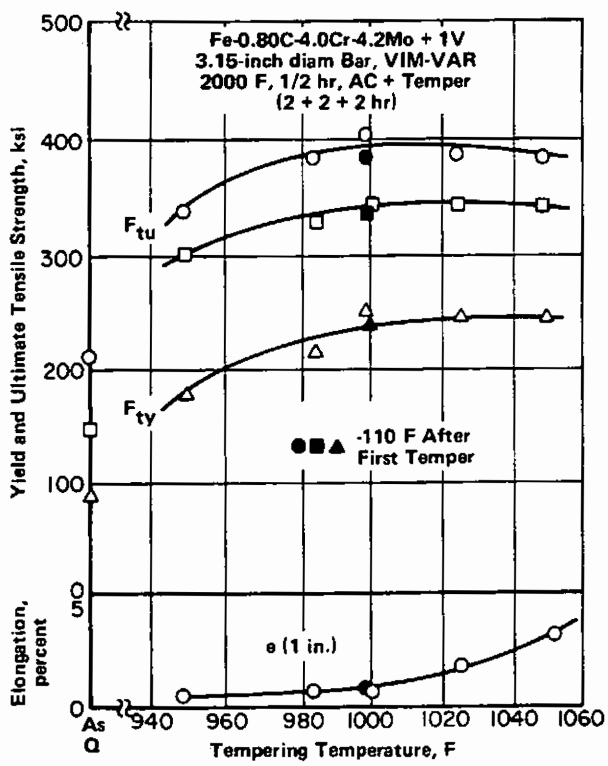

FIGURE 3.0211. EFFECT OF TEMPERING TEMPERATURE ON TENSILE PROPERTIES OF VIM-VAR BAR (13, FIGURES 5 AND 7)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

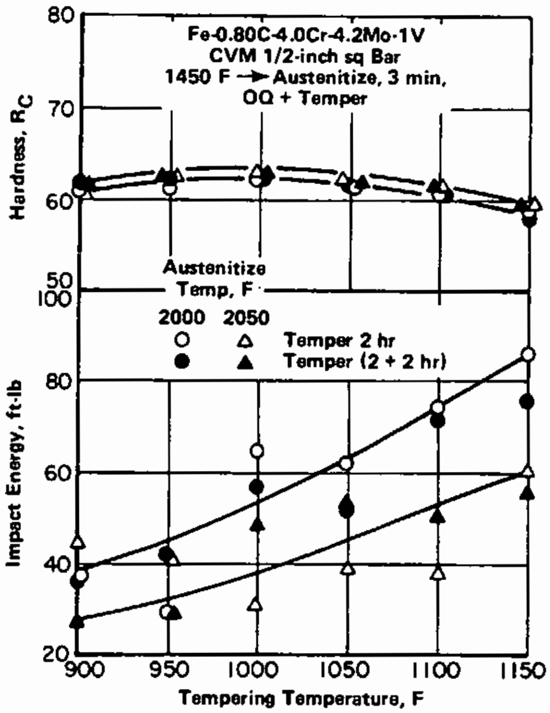

FIGURE 3.0231. EFFECT OF TEMPERING TEMPERATURE ON THE UNNOTCHED IZOD IMPACT ENERGY OF CVM BAR AUSTENITIZED AT 2000 OR 2050 F (6)

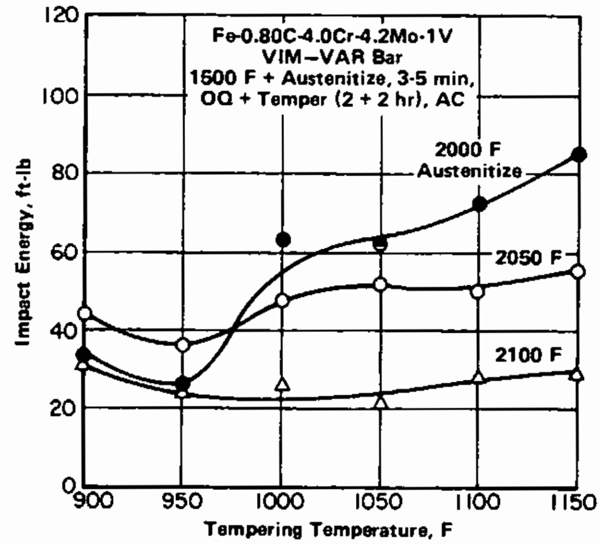

FIGURE 3.0232. EFFECT OF TEMPERING TEMPERATURE ON THE UNNOTCHED IZOD IMPACT ENERGY OF VIM-VAR BAR AUSTENITIZED AT SEVERAL TEMPERATURES (4)

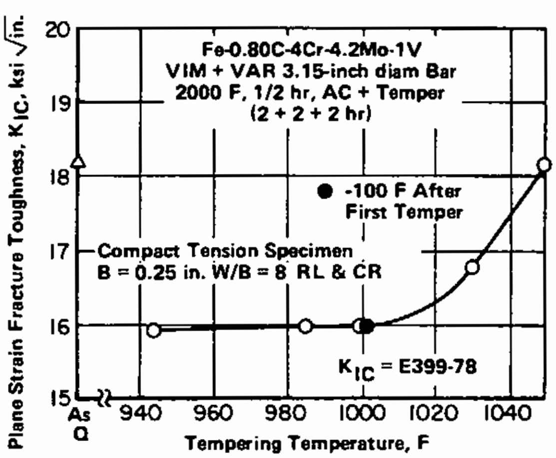

FIGURE 3.02722. EFFECT OF TEMPERING TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF BAR (13, FIGURE 11)

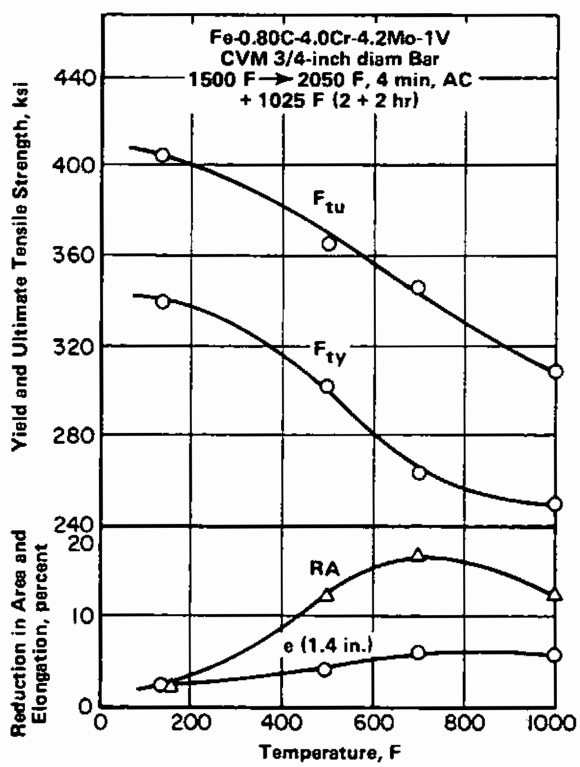

FIGURE 3.0311. EFFECT OF ELEVATED TEMPERATURES ON THE TENSILE PROPERTIES OF CVM BAR (10)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

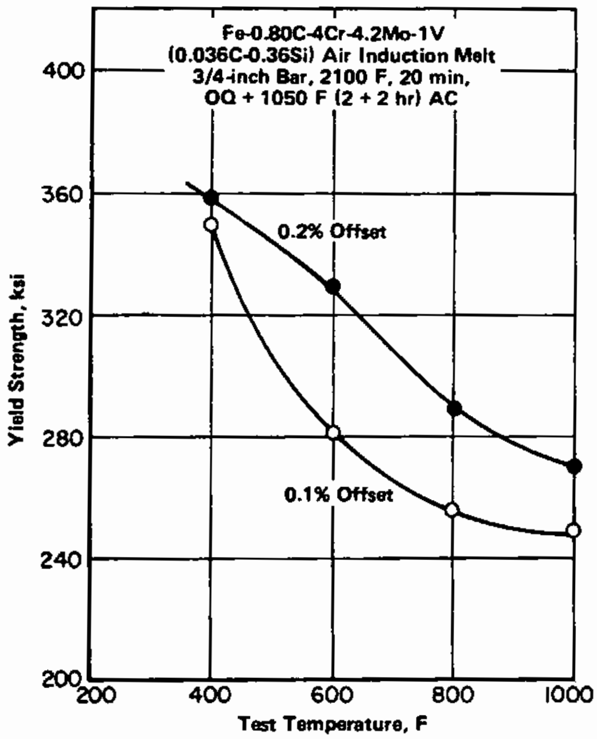

FIGURE 3.0321. EFFECT OF TEST TEMPERATURE ON COMPRESSION YIELD STRENGTH OF AIR INDUCTION MELTED BAR (5, TABLE 6)

Alloy	Fe-0.80C-4.0Cr-4.2Mo-1V	
Form	0.375-inch diam Cylinders	
Condition	8-10 μin. Finish See Table 1.082	
Rolling Contact Fatigue	700,000 Max Hertz Pressure, 20,000 Cycles/min, Lubricant MIL-L-7808, Wheel Finish 8-10 μin. Ground	
Melt Practice	AM + VAR	VIM + VAR
B_{10}, 10^6 Cycles[a]	2.03	4.18
B_{50}, 10^6 Cycles	4.25	7.19
B_1, 10^6 Cycles[b]	0.81	2.13
Weibull Slope	2.52	3.48
Correlation Coefficient	0.93	0.96

(a) B_1, B_{10}, and B_{50} – The number of cycles below which 1%, 10%, and 50%, respectively, of small type failures will occur.
(b) Extrapolated.

TABLE 3.052. COMPARATIVE PERFORMANCE OF AM+VAR AND VIM+VAR MATERIAL IN A ROLLING CONTACT FATIGUE TEST (7p, 1330)

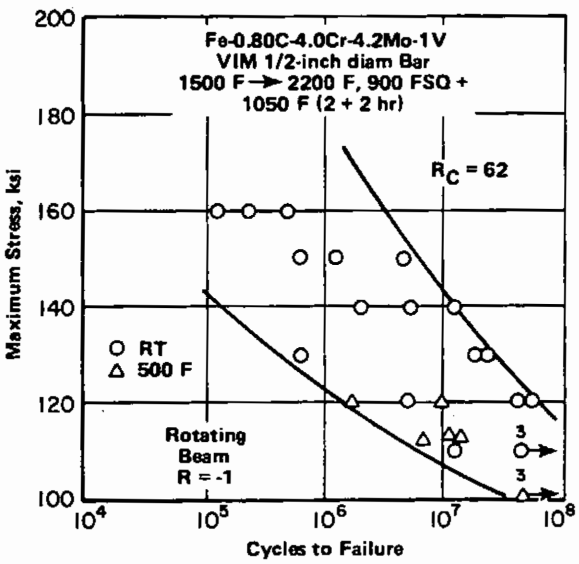

FIGURE 3.053. S-N CURVES FOR VIM BAR AT ROOM TEMPERATURE AND 500 F

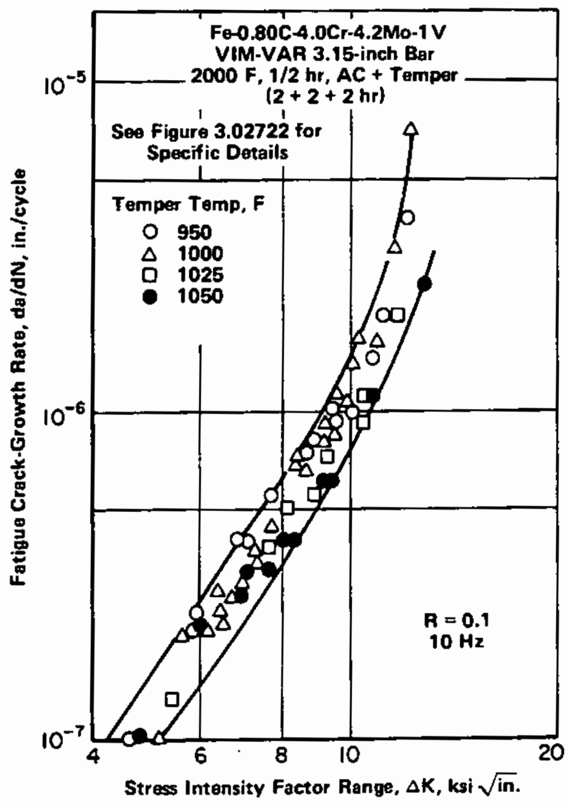

FIGURE 3.054. CRACK PROPAGATION RATE AS FUNCTION OF STRESS INTENSITY FACTOR RANGE FOR VIM-VAR BAR (13, FIGURE 15)

	Fe
0.8	C
4	Cr
4	Mo
1	V
0.2	Si

M50

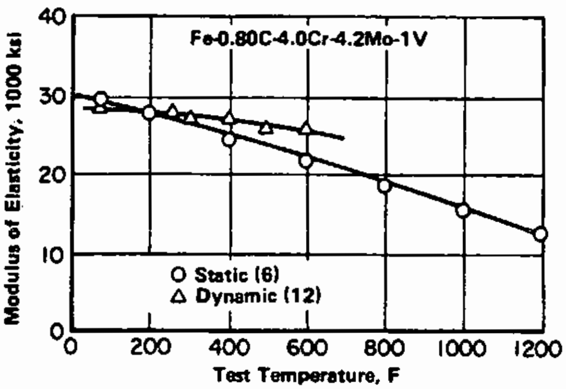

FIGURE 3.0621. EFFECT OF TEST TEMPERATURE ON MODULUS OF ELASTICITY (6, 12)

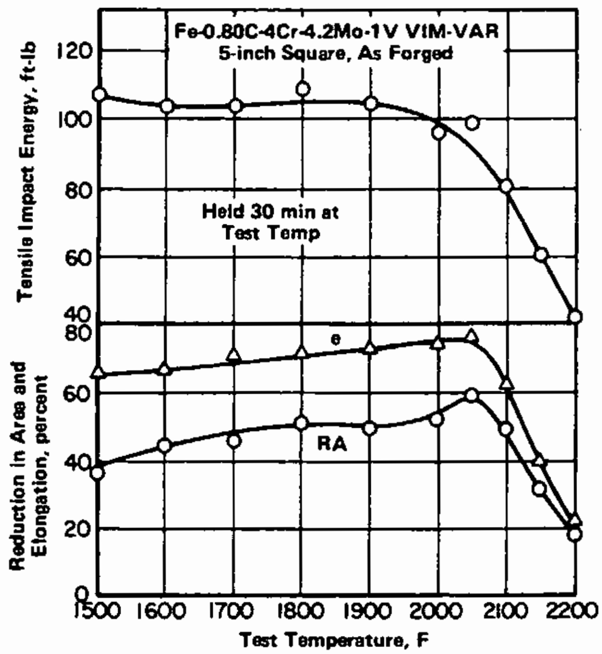

FIGURE 4.013. EFFECT OF HIGH TEST TEMPERATURE ON TENSILE IMPACT ENERGY OF VIM-VAR AS FORGED BILLET (4)