18 per cent nickel maraging steels

Engineering properties

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INCO databooks

Inco, the leading producer and marketer of nickel, conducts research and development programmes on nickel alloys, products and processes, establishing engineering and performance data. This knowledge is collated in a library of INCO databooks, which are freely available.

Conversion factors for stress and impact energy units

SI metric units have been adopted as the standard throughout this publication.
To assist readers who may be more familiar with other units to which they have been accustomed, factors are given below for conversion of the more important of these to SI metric units and vice versa.

Stress units:

1 tonf/in^2 = 15.44 N/mm^2
1 kgf/mm^2 = 9.807 N/mm^2
10^3lbf/in^2 = 6.895 N/mm^2
1 N/mm^2 = 0.0647 tonf/in^2
or 0.102 kgf/mm^2
or 0.145 10^3lbf/in^2
or 0.1 hbar

1 GN/m^2 = 1 GPa
or 1 KN/mm^2
or 0.145 10^6lbf/in^2
or 0.102 10^3kgf/mm^2
or 100 hbar

Note that the newton per square millimetre (N/mm^2), meganewton per square metre (MN/m^2) and megapascal (MPa) SI units of stress are arithmetically identical.

Impact energy units:

1 ft lbf = 1.356 J
1 kgf m = 9.807 J
1 J = 0.7375 ft lbf
or 0.102 kgf m
1 J (Charpy V impact) = 0.1275 kgf m/cm^2
1 J (Charpy U impact) = 0.2039 kgf m/cm^2
1 J (DVM impact) = 0.1457 kgf m/cm^2
1 J (Mesnager impact) = 0.1275 kgf m/cm^2

Plane strain fracture toughness (K_{1c}) units:

1 MNm$^{-3/2}$ = 0.910 10^3lbf in$^{-3/2}$ (ksi$\sqrt{\text{in}}$)
or 31.623 Nmm$^{-3/2}$
or 3.225 kgf mm$^{-3/2}$ (kp mm$^{-3/2}$)
or 3.162da Nmm$^{-3/2}$ (hbar$\sqrt{\text{mm}}$)
1 ksi$\sqrt{\text{in}}$ =1.0988 MNm$^{-3/2}$
or 34.748 Nmm$^{-3/2}$
or 3.543 kgf mm$^{-3/2}$ (kp mm$^{-3/2}$)
or 3.475 da Nmm$^{-3/2}$ (hbar$\sqrt{\text{mm}}$)

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Contents

Inco Europe Limited

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Introduction

The development of the nickel maraging steels began in the Inco research laboratories in the late 1950s and was based on the concept of using substitutional elements to produce age-hardening in a low-carbon iron-nickel martensitic matrix. Hence the term 'maraging' was given to them to signify this strengthening mechanism.

The work led to the discovery that balanced additions of cobalt and molybdenum to iron-nickel martensite gave a combined age-hardening effect appreciably greater than the additive effects of these elements used separately. Furthermore, the iron-nickel-cobalt-molybdenum matrix was found to be amenable to supplemental age-hardening by small additions of titanium and aluminium. Thus the 18 per cent nickel-cobalt-molybdenum family of maraging steels was developed.

There are basically four wrought commercial maraging steels of the 18 per cent nickel family and one cast grade currently available from special steel manufacturers. The nominal compositions and 0.2 per cent proof stress values are presented in Table 1. The reader should note that the numbers ascribed to the various grades in this publication correspond to the nominal proof stresses given in SI units, whereas the identical grades in some countries have designations with lower numbers corresponding to the units traditionally used for proof stress values, e.g., in the U.S.A. the maraging steel numbers refer to the nominal 0.2 per cent proof stress values in kilopounds/inch^2.

These steels have been designed to develop high proof stress with optimum toughness for the various strength levels. In contrast to conventional ultra-high-strength alloy steels in which carbon is an essential constituent and the formation of hard carbon-martensite is necessary for the development of high strength, nickel maraging steels have a very low carbon content and their high strengths are derived by age-hardening of relatively soft low-carbon martensite. In consequence, the toughness of the maraging steels is distinctly superior to that of conventional steels at the same strength levels, as shown for example by the comparison of notched tensile strengths of the several steels illustrated in Figure 1.

Because the physical metallurgy and properties of maraging steels are unique they have many commercial advantages which are summarized in Table 2 (*page 4*). Since the production of the first commercial heat in December, 1960 the range of applications has steadily grown and is ever widening. A sample of typical applications is given in Table 3 (*page 4*).

Commercial and national specifications

The composition ranges developed by Inco to provide several combinations of properties are detailed in Table 4 (*page 4*). These have formed the basis for commercial production throughout the world with minor variations sometimes being adopted in the manufacture of proprietary designated grades and in some authoritative specifications. Tables 5 and 6 (*pages 5–9*) summarize the requirements of several commercial specifications used in various countries as national and international standards.

Table 1. *Nickel maraging steels.*

Type	Nominal 0.2% proof stress					Nominal composition. Weight %				
	N/mm^2	10^3lbf/in^2	tonf/in^2	kgf/mm^2	hbar	Ni	Co	Mo	Ti	Al
18Ni1400	1400	200	90	140	140	18	8.5	3	0.2	0.1
18Ni1700	1700	250	110	175	170	18	8	5	0.4	0.1
18Ni1900	1900	280*	125	195	190	18	9	5	0.6	0.1
18Ni2400	2400	350	155	245	240	17.5	12.5	3.75	1.8	0.15
17Ni1600(cast)	1600	230	105	165	160	17	10	4.6	0.3	0.05

* *This steel is generally designated the 300 ksi grade in the U.S.A.. the 0.2 per cent proof stress normally ranging from 260,000 to 300,000 lbf/in^2.*

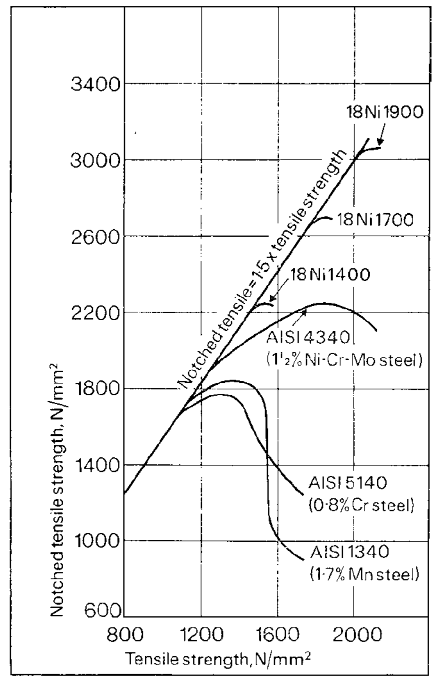

Figure 1. *The toughness of maraging steels is demonstrated by their adherence to the relationship Notched tensile strength/Tensile strength ≏ 1.5, up to higher strength levels than for conventional steels.*

Melting practice

Nickel maraging steels are generally produced by vacuum melting, or by a double melting and refining procedure involving both air and vacuum melting, while double vacuum melting is often employed. Whatever the process the objective is (i) to hold composition within the prescribed limits with close control over impurities, (ii) minimize segregation, (iii) obtain a low gas content and a high standard of cleanliness. The degree to which these objectives are reached will influence the toughness and to some extent the strength of finished mill products.

Small amounts of impurities can decrease the toughness significantly. In particular sulphur should be kept as low as possible and silicon and manganese must not exceed a combined level of 0.2 per cent. The elements P, Pb, Bi, O_2, N_2 and H_2 are all maintained at low levels in good melting practice.

Ingot sizes and shapes and pouring practice should be selected to ensure Sound ingots with minimum alloy segregation.

Table 2. *Advantages of nickel maraging steels.*

Excellent Mechanical Properties	Good Processing and Fabrication Characteristics	Simple Heat Treatment
1. High strength and high strength-to-weight ratio. 2. High notched strength. 3. Maintains high strength up to at least 350°C. 4. High impact toughness and plane strain fracture toughness.	1. Wrought grades are amenable to hot and cold deformation by most techniques. Work-hardening rates are low. 2. Excellent weldability. either in the annealed or aged conditions. Pre-heat not required. 3. Good machinability. 4. Good castability.	1. No quenching required. Softened and solution treated by air cooling from 820–900°C. 2. Hardened and strengthened by ageing at 450–500°C. 3. No decarburization effects. 4. Dimensional changes during age hardening are very small – possible to finish machine before hardening. 5. Can be surface hardened by nitriding.

Table 3. *Typical applications.*

Aerospace	Tooling and Machinery	Structural Engineering and Ordnance
Aircraft forgings (e.g., undercarriage parts. wing fittings). Solid-propellant missile cases. Jet-engine starter impellers. Aircraft arrestor hooks. Torque transmission shafts. Aircraft ejector release units.	Punches and die bolsters for cold forging. Extrusion press rams and mandrels. Aluminium die-casting and extrusion dies. Cold reducing mandrels in tube production. Zinc-base alloy die-casting dies. Machine components: gears index plates lead screws	Lightweight portable military bridges. Ordnance components. Fasteners.

Table 4. *Composition ranges – weight per cent – of the 18 per cent Ni-Co-Mo maraging steels.*[(1)]

	Wrought				Cast
Grade	18Ni1400	18Ni1700	18Ni1900	18Ni2400	17Ni1600
Nominal 0.2% proof stress					
N/mm^2 (MPa)	1400	1700	1900	2400	1600
$tonf/in^2$	90	110	125	155	105
$10^3 lbf/in^2$	200	250	280[(2)]	350	230
kgf/mm^2	140	175	195	245	165
hbar	140	170	190	240	160
Ni	17–19	17–19	18–19	17–18	16–17.5
Co	8.0–9.0	7.0–8.5	8.0–9.5	12–13	9.5–11.0
Mo	3.0–3.5	4.6–5.1	4.6–5.2	3.5–4.0	4.4–4.8
Ti	0.15–0.25	0.3–0.5	0.5–0.8	1.6–2.0	0.15–0.45
Al	0.05–0.15	0.05–0.15	0.05–0.15	0.1–0.2	0.02–0.10
C max.	0.03	0.03	0.03	0·01	0.03
Si max.	0.12	0.12	0.12	0.10	0.10
Mn max.	0.12	0.12	0.12	0.10	0.10
Si+Mn max.	0.20	0.20	0.20	0.20	0.20
S max.	0.010	0.010	0.010	0.005	0.010
P max.	0.010	0.010	0.010	0.005	0.010
Ca added	0.05	0.05	0.05	none	none
B added	0.003	0.003	0.003	none	none
Zr added	0.02	0.02	0.02	none	none
Fe	Balance	Balance	Balance	Balance	Balance

(1) The composition ranges given are those originally developed by Inco which broadly cover current commercial practice. Slight changes in these ranges have been made in some national and international specifications.

(2) See footnote of Table 1.

Castings

The 17Ni1600 grade developed for castings has slightly different composition compared with the wrought grades (see Tables 1 and 4) in order to minimize retention of austenite that might otherwise occur in more highly alloyed regions of the structure due to micro-segregation which tends to persist in the absence of hot working. This steel has good fluidity and pouring temperatures much higher than 1580°C are generally not desirable if segregation is to be minimized.

Mechanical properties of wrought maraging steels

The usual heat treatment applied to the 18Ni1400, 1700 and 1900 grades of maraging steels comprises solution annealing at 820°C followed by ageing 3 hours at 480°C. Similar annealing is applied to the 18Ni2400 steel, but ageing is effected by heating for 3 hours at 510°C or longer times at 480°C. The normally expected mechanical properties after these treatments are given in Table 7 (*page 10*) while Tables 8–11 (*pages 10–11*) present typical mechanical test data for material of various section sizes obtained from production casts.

Elastic and plastic strain characteristics

The uniaxial tensile deformation behaviour of maraging steels is shown by the stress-strain and true stress-true strain curves of Figs. 2 and 3 (*page 11*), respectively. Plastic yielding occurs at stresses of the order of 95 per cent of the ultimate tensile stress. The strain hardening moduli of maraging steels subjected to plastic strain are:

Steel Type	*Strain Hardening Modulus*
18Ni1400	724 N/mm^2
18Ni1700	758 N/mm^2
18Ni1900	793 N/mm^2
18Ni2400	827 N/mm^2

Fracture toughness

The ability of metallic alloys to resist rapid propagation of a crack or unstable fracture originating at an imperfection (i.e., brittle fracture), particularly in materials of high strength, is of great importance in determining their utility for engineering purposes. As with other high-strength alloys, various methods have been employed to evaluate the fracture characteristics of maraging steels with the results described in the sections on pages 10 and 12.

Table 5. *18 per cent nickel maraging steels. Chemical compositions quoted in national and international specifications.*

Country	Specifying body	Specification	Method of manufacture	Form of product	Composition, per cent					
					Ni	Co	Mo	Ti	C max.	Other
United Kingdom	Ministry of Technology. Aerospace Material Specification.	DTD 5212 (Jan. 1969)	Double vacuum melted (induction + vacuum arc remelt)	Billets Bars Forgings	17.0–19.0	7.0–8.5	4.6–5.2	0.30–0.60	0.015	a, c, d
		DTD 5232 (Aug. 1969)	Single vacuum melted (air melt + vacuum arc remelt)							
International	Association Internationale des Constructeurs de Material Aerospatiale	AICMA–FE–PA95 (provisional recommenda-tion Dec. 1965)	Vacuum melted or vacuum remelted	Bars Plates Forgings	17.0–19.0	7.5–8.5	4.6–5.2	0.30–0.50	0.03	a, b
Germany	Normenstelle Luftfahrt. (Aeronautical standards)	I.6359 (Nov. 1973)	Consumable electrode remelt	Sheet Plate Bars Forgings	17.0–19.0	7.0–8.5	4 6–5 2	0.30–0.60	0.03	a, c
		I.6354 (Nov. 1973)	Consumable electrode remelt	Bars Forgings	17.0–19.0	8.0–9.5	4.6–5.2	0.60–0.90	0.03	a, c
		I.6351 (Draft specification Aug. 1973)	Melted and cast under argon or vacuum* (Shaw or precision casting methods)	Precision castings	16.0–18.0	9.5–11.0	4.5–5.0	0.15–0.45	0.03	a, c
U.S.A.	A.S.T.M.	A538-72a: Grade A	Electric furnace air melt. Vacuum arc remelt. Air – or vacuum – induction melt	Plates	17.0–19.0	7.0–8.5	4.0–4.5	0.10–0.25	0.03	a, e
		Grade B			17.0–19.0	7.0–8.5	4.6–5·1	0.30–0.50	0.03	a, e
		Grade C			18.0–19.0	8.0–9.5	4.6–5.2	0.55–0.80	0.03	a, e
		A579-70: Grade 71	Electric arc air melt. Air – or vacuum – induction melt. Consumable electrode remelt or combination of these	Forgings	17.0–19.0	8.0–9.0	3.0–3.5	0.15–0.25	0.03	a, f
		Grade 72			17.0–19.0	7.5–8.5	4.6–5.2	0.30–0.50	0.03	a, f
		Grade 73			18.0–19.0	8.5–9.5	4.6–5.2	0.50–0.80	0.03	a, f
	S.A.E. Aerospace Material Specification	AMS 6512 (May 1970)	Vacuum arc remelt or consumable electrode remelt in air using vacuum induction melted electrodes	Bars Forgings Tubes Rings	17.0–19.0	7.0–8.5	4.6–5.2	0.30–0.50	0.03	a, e, g
		AMS 6514 (May 1970)			18.0–19.0	8.5–9.5	4.6–5.2	0.50–0.80	0.03	a, e, g
		AMS 6520 (May 1969)		Sheet Strip Plate	17.0–19.0	7.0–8.5	4.6–5.2	0.30–0.50	0.03	a, e, g
		AMS 6521 (May 1969)			18.0–19.0	8.5–9.5	4.6–5.2	0.50–0.80	0.03	a, e, g

** Casting in air may be adopted if agreed between supplier and purchaser.*
a. Si 0.10 max. Mn 0.10 max. S 0.010 max, P 0.010 max. Al 0.05–0.15.
b. B 0.003 max, Zr 0.02 max.
c. Ca, B and Zr may be added in amounts of 0.05 per cent max, 0.003 per cent max, and 0.02 per cent max, respectively.
d. Cr 0.25 max (DTD 5212) and 0.20 max (DTD 5232).
e. The following specified additions shall be made to the melt: B 0.003 per cent. Zr 0.02 per cent and Ca 0.05 per cent.
f. The following specified additions shall be made to the melt: B 0.003 percent. Zr 0.02 percent and Ca 0.06 percent.
g. Cr 0.5 max. Cu 0.50 max.

Table 6. *18 per cent nickel maraging steels. Mechanical properties quoted in the specifications listed in Table 5. (Minimum values except as stated otherwise)*

Specification	Form of Product	Heat treatment condition	Hardness	0.2% proof stress				Tensile strength				Elongation %		Reduction of area %		Impact energy value				Radius for 180° bend test
				Longit.		Transv.		Longit.		Transv.		Longit.	Transv.	Longit.	Transv.	Test-piece	J	ft lbf	kgf/cm²	
				N/mm² (MPa)	† h bar	N/mm² (MPa)	† h bar	N/mm² (MPa)	† h bar	N/mm² (MPa)	† h bar	Lo = 5.65√So								
DTD5212	Billets	S.A. 810°–830°C	≤ 321HB ≤ 355HV	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Bars Forgings	S.A. 810°–830°C + ≥ 3h 475°–485°C	520–620HV	1700	170	1700	170	1800–2000	180–200	1800–2000	180–200	8	5	40	25	Izod		†		–
																Longit. Transv.	24 11	18 8	– –	
																KCU	J/cm²			
																Longit. Transv.	39 20	– –	4(a) 2(a)	
DTD5232	Billets	S.A. 810°–830°C	≤ 321HB ≤ 335HV	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Bars Forgings	S.A. 810°–830°C+ 3h 475°–485°C	520–620HV	1700	170	1700	170	1800–2000	180–200	1800–2000	180–200	6	4	35	20	Izod		†		–
																Longit. Transv.	16 8	12 6	– –	
																KCU	J/cm²			
																Longit. Transv.	29 20	– –	3(a) 2(a)	
AICMA-FE-PA95					† kgf/mm²				† kgf/mm²								J/cm²			
	Bar test-coupon, 16 mm dia.	S.A. 810°–830°C+ 3h 475°–485°C	–	1620	165	–	–	1720–1910	175–195	–	–	8	–	45	–	KCU Longit.	39	–	4	–
	Bars	S.A. 810°–830°C (as-supplied)	331HB max.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Plates		350HB max.																	
	Forgings		–																	
	Bar ≤ 100 mm dia. Forgings	S.A. 810°–830°C+ 3h 475°–485°C	–	1620	165	–	–	1720–1910	175–195	–	–	6	4	40	25	KCU Longit.	20	–	† 4	–
	Plate ≤ 10 mm thickness	S.A. 810°–830°C+ 3h 475°–485°C	–	1620	165	–	–	1720–1910	175–195	–	–	5	–	–	–	–	–	–	–	≤ 3 × thickness for plate ≤ 8 mm thick

Normenstelle Lultfahrt I.6359: Werkstoff Nr. I.6359.9	Sheet 0.5–6.0mm thickness Plate > 6 ≤ 10mm thickness (cold- or hot-rolled, polished or descaled)	S.A. 810°–830°C, air-cooled	≤ 350HV	† N/mm² (MPa)		† N/mm² (MPa)		† N/mm² (MPa)		† N/mm² (MPa)										
				–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3 × thickness for sheet or plate ≤ 8 mm thick (transv. test)
Werkstoff Nr. I.6359.4	Sheet and plate:	S.A. and aged 3h 470°–490°C air-cooled	(480 HV)	–	–	1620	–	–	–	1720	–	–	Lo = 50 mm (f)							
	2–3 mm thick												3	–	–	–	–	–	–	–
	> 3 ≤ 6 mm												4	–	–	–	–	–	–	–
	> 6 ≤ 10 mm												5	–	–	–	–	–	–	–
Werkstoff Nr. I.6359.9	Bar 2–100 mm dia. Forgings ≤70 mm thickness	S.A. 810° 830°C, air-cooled	≤ 353HB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Werkstoff Nr. I.6359.4	Bar 2–100 mm dia. Forgings ≤ 70 mm thickness	S.A. and aged 3h 470°–490°C, air-cooled	(480 HV)	1620	–	1620	–	1720	–	1720	–	Lo = 5.65 √So		40	25	DVM	† J	–	–	–
												6	4				30 Longit. 20 Transv.	–	–	
Normensielle Luftfahrt I.6354: Werkstoff Nr. I.6354.9	Bar 2–100 mm dia. Forgings ≤ 70 mm thickness	S.A. 810°–830°C, air-cooled	≤ 353HB	† N/mm² (MPa)		† N/mm² (MPa)		† N/mm² (MPa)		† N/mm² (MPa)		Lo = 5.65 √So								
				–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Werkstoff Nr. I.6354.4	Bar 2–100 mm dia. Forgings ≤ 70 mm thickness	S.A. and aged 3–5h 480°–500°C, air-cooled	(542 HV)	1910	–	1910	–	1960	–	1960	–	4.5	3.5	30	20	DVM	† J	–	–	–
																	20 Longit. 12 Transv.	–	–	–

Table continued on pages 8 & 9

Table 6. *continued*

Specification	Form of Product	Heat treatment condition	Hardness	0.2% proof stress Longit.		0.2% proof stress Transv.		Tensile strength Longit.		Tensile strength Transv.		Elongation % Longit.	Elongation % Longit.	Reduction of area % Transv.	Reduction of area % Longit.	Impact energy value Test-piece	J	ft lbf	kgf/ cm^2	Radius for 180° bend test
Normensteile L uftfahrt I.6531; Werkstoff Nr. I.6531.9				Test-piece obtained from cast test coupon																
				N/mm^2 † (MPa)				N/mm^2 † (MPa)				Lo = 5.65 $\sqrt{So}$								
	Un-machined castings ≤ 50 mm section thickness	Homogenized 1150° ± 15°C, air-cooled	(≤ 32 HRC)	(600)				(900)				(8)								
																Charpy V-notch				
																	J			
Werkstoff Nt. I.6531.4	Finished cast parts ≤ 25 mm	Homogenized and aged 3 h 475°–495°C, an-cooled	(52 HRC)	14.50				1600				4		10			(16)			
	> 25 ≤ 50mm section thickness			1450				1600				3		8			(14)			
AS TM A538-72a:				† N/mm^2 (MPa)	† 10^3 lbf/ in^2	† N/mm^2 (MPa)	† 10^3 lbf/ in^2	† N/mm^2 (MPa)	† 10^3 lbf/ in^2	† N/mm^2 (MPa)	† 10^3 lbf/ in^2	Lo = 2 in. or 50 mm				–	–	–	–	–
Grade A	Plate	S.A. 815°–982 C(b) + 3h 468°–500°C	–	1380–1620	200–235	1380–1620	200–235	1450	210	1450	210	8	8	40(c) 35(d)	40(c) 35(d)					
Grade B	Plate		–	1580–1790	230–260	1580–1790	230–260	1650	240	1650	240	6	6	35(c) 30(d)	35(c) 30(d)	–	–	–	–	–
Grade C	Plate		–	1900–2100	215–305	1900–2100	275–305	1930	280	1930	280	6	6	30(c) 25(d)	30(c) 25(d)	–	–	–	–	–
												Lo = 5.65 $\sqrt{So}$				Charpy V -notch				–
ASTM A579-70(e):																	† J	† ftlbf		
Grade 71	Forgings	S.A. and aged	–	1380	200	–	–	1450	210	–	–	12	–	55	–	–	48	35	–	–
Grade 72	Forgings		–	1725	250	–	–	1760	255	–	–	10	–	45	–	–	21	20	–	–
Grade 73	Forgings		–	1800	275	–	–	1930	280	–	–	9	–	40	–	–	20	15	–	–

SAE AMS 6512	Bars Forgings Tubes Rings Cross-section Thickness:	S.A.816°– 927°C	<34HRC <321HB†	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
																Charpy V-notch				
					†		†		†		†						J	† ftlbf		
	< 2.5 in. (64 mm	S.A.816°– 927°C + 3–6h 477°–488°C	>52HRC† >560HV	1860	270	–	–	1930	280	–	–	5	–	30	–	Longit.	14	10	–	–
	2.5–4.0 in. (64–102 mm)			1860	270	1860	270	1930	280	1930	280	5	4	30	25	Longit. Transv.	11 8	8 6	– –	–
	4.0–10.0 in. (102–254 mm)			1860	270	1860	270	1900	275	1900	275	4	2	25	20	Longit. Transv.	8 5	6 4	– –	–
	> 10.0 in. (254 mm)			to be agreed between purchaser and vendor.																
SAE AMS 6520	Sheet Strip Plate	S.A.802°– 830°C	<34HRC† <321HB	–	† –	–	† –	–	† –	–	† –	–	–	–	–	–	–	–	–	–
	≤ 9 in. wide (229 mm)	S.A. 802°– 830°C + 3–5 h 471°–488°C	>48HRC† >500HV	1690	245	–	–	1760	255	–	–	(g)	–	–	–	Fracture toughness values are negotiated between purchaser and vendor. The ASTM sharp-notch test for high strength sheet materials is suggested				–
	> 9 in. wide (229 mm)			–	–	1690	245	–	–	1760	255	–	(g)	–	–					–
SAE AMS 6521	Sheet Strip Plate	S.A.802°– 830°C	<34HRC† <321HB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	≤ 9 in. wide (229 mm)	S.A. 802°– 830°C + 3–5 h 477°–488°C	>50HRC† >530HV	1860	270	–	–	1930	280	–	–	(g)	–	–	–	Fracture toughness values are negotiated as stated above				–
	< 9 in. wide (229 mm)			–	–	1860	270	–	–	1930	280	–	(g)	–	–					–

† *Specified value. Other values have been obtained by conversion.*

S.A. Solution annealed.

( ) *figures in parentheses are approximate values to be expected.*

(a) *The KCU test is not a mandatory requirement of the specification, but impact values which may be expected are quoted in the specification for guidance.*

(b) *A double solution anneal is permissible. It is recommended that the lowest temperature is used, within the range specified. which will effect recrystallization at the mid-thickness position.*

(c) *Round test-piece. for plate thickness > 0.75 in (19 mm) a standard 0 5 in (12.7 mm) diameter test-piece shall be used. for plate thickness ≤ 0.75 in (19 mm) sub-size round test-pieces or rectangular test-pieces may be used.*

(e) *Vacuum melting is normally required to achieve the listed properties, The indicated 0.2 per cent proof stress values can usually be achieved at a depth = ¼ thickness in section sites up to 12 in (305 mm) in the direction of maximum hot- working. Because of variations in forging configuration and processing it does not follow that the ductility and impact strengths listed can always be obtained at these depths.*

(f) *Lo = 5.65√ So for plate.*

(g) *The minimum elongation value specified varies according to the thickness of the product and the test-piece gauge length as shown in the table below:*

Product thickness: inch† mm	<0.030 <0.8	0.030–0.045 0.8–1.1	>0.045–0.065 >1.1–1.6	>0.065–0.090 >1.6–2.3	>0.090–0.125 >2.3–3.2	>0.125–0.250 >3.2–6.4	>0.250–0.375 >6.4–9.5	>0.375 >9.5
	Minimum elongation, per cent							
Test-piece gauge length: 2 in. (51 mm) or 4D	–	–	–	2.5	3.0	4.0	5.0	6.0
1 in. (25 mm)	–	–	2.0	5.0	6.0	8.0	–	–
0.5 in. (13 mm)	1.0	2.0	–	–	–	–	–	–

Table 7. *Mechanical properties of wrought 18 per cent nickel maraging steels.*

Property	18Ni1400	18Ni1700	18Ni1900	18Ni2400
	Solution-annealed 1 h 820°C			
0.2% proof stress, N/mm^2	800	800	790	830
Tensile strength, N/mm^2	1000	1010	1010	1150
Elongation, Lo=4.5$\sqrt{}$So., %	17	19	17	18
Reduction of Area, %	79	72	76	70
Hardness, HRC	27	29	32	35
	Solution-annealed 1h 820°C, aged 3h 480°C			Solution-annealed 1h 820°C, aged 12h 480°C
	Normal ranges of properties			Typical properties
0.2% proof stress, N/mm^2	1310–1550	1650–1830	1790–2070	2390
Tensile strength, N/mm^2	1340–1590	1690–1860	1830–2100	2460
Elongation, Lo=4.5$\sqrt{}$So., %	6–12	6–10	5–10	8
Reduction of Area, %	35–67	35–60	30–50	36
Modulus of Elasticity (E), GN/m^2	181	186	190	191–199
Modulus of Rigidity (G), (torsional shear), GN/m^2	–	71–4	–	74.5
Hardness, HRC	44–48	48–50	51–55	56–59
Charpy V-notch impact value, J(daJ/cm^2)	35–68 (4.4–8.5)	24–45 (3.0–5.6)	16–26 (2.0–3.3)	11 (1.4)
Poissons ratio	0.264	0.30	0.30	0.26
Notched tensile strength (Kt =10) N/mm^2	2390	2350–2650	2700–3000	1430
(Kt=3.5) N/mm^2	–	–	–	2700

Table 8. *Typical mechanical properties of double vacuum melted 18Ni1400 managing steel.*
(Solution-annealed and aged 3h 480°C, except as stated otherwise)

Section Size	Direction of test	0.2% proof stress N/mm^2	Tensile Strength N/mm^2	Elong. Lo = 5.65$\sqrt{}$So %	R of A %	Charpy V-notch impact value J	Charpy V-notch impact value daJ/cm^2
150 × 150mm	Longit.	1450	1480	12	65	81	10.1
150 × 150mm*	Longit.	1510	1540	12	64	91	11.4
100 × 100mm	Longit.	1420	1470	12	68	73	9.1
100 × 100mm*	Longit.	1450	1510	13	67	92	11.5
75 × 75mm	Longit.	1420	1450	13	70	115	14.4
150 × 150mm	Transv.	1390	1470	10	55	38	4.8
150 × 150mm-	Transv.	1450	1510	10	55	35	4.4

**Aged 10h 460/465°C (Data by courtesy of Firth Brown Limited, Sheffield, U.K.)*

Table 9. *Typical mechanical properties of double vacuum melted 18Ni1700 managing steel.*
(Solution-annealed and aged 3h 480°C)

Section Size	Direction of test	0.2% proof stress Nrmm^2	Tensile Strength N/mm^2	Elong. Lo = 5.65$\sqrt{}$So %	R of A %	Izod impact value J
300 x 300mm	Transv.	1730	1860	7	35	20
125mm dia.	Transv.	1750	1860	7	35	20
100mm dia.	Transv.	1780	1860	6	30	16
75mm dia.	Transv.	1800	1860	5	30	14
100mm dia.	Longit.	1820	1980	9	50	27
75mm dia.	Longit.	1840	1960	9	50	41
50mm dia.	Longit.	1730	1860	10	55	41
25mm dia.	Longit.	1730	2000	12	55	47
13mm dia.	Longit.	1800	1960	12	55	47

(Data by courtesy of Firth Brown Limited. Sheffield, U.K.)

Impact transition temperature

The temperature range of transition from ductile to brittle fracture in notched impact tests conducted at various temperatures, and the corresponding change in impact energy absorption values, provide a comparative assessment of the fracture behaviour of various materials. In the case of maraging steels the fall in energy absorption values with decreasing temperature is small and gradual with useful toughness being retained at low temperatures, as shown in Figure 4. This lack of an abrupt transition in impact energy absorption with fall of temperature is a significant measure of the relatively high resistance of these steels to unstable fracture propagation.

Notched tensile properties

18 per cent Ni managing steels exhibit high ratios of notched tensile strength to tensile strength, these being unobtainable in conventional steels at the same high strength levels. Figure 5 presents notched tensile data for bar and sheet. In general, longitudinal tests on bar material of the 18Ni1400, 1700 and 1900 grades give NTS/UTS ratios of about 1.5. Deviations below that value shown for the 18Ni1700 and l8Ni1900 steels are, in general, from the transverse direction of large forgings. The values for sheet follow a ratio of about 1.0, although lower ratios may be obtained depending on processing variables. Notched tensile strengths of sheet at temperatures as low as –196°C are only 10–20 per cent lower than the room-temperature values. This retention of high notched tensile strength at low

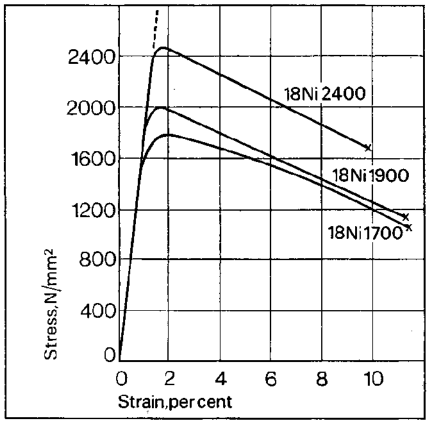

Figure 2. *Tensile stress-strain curves of maraged steels.*

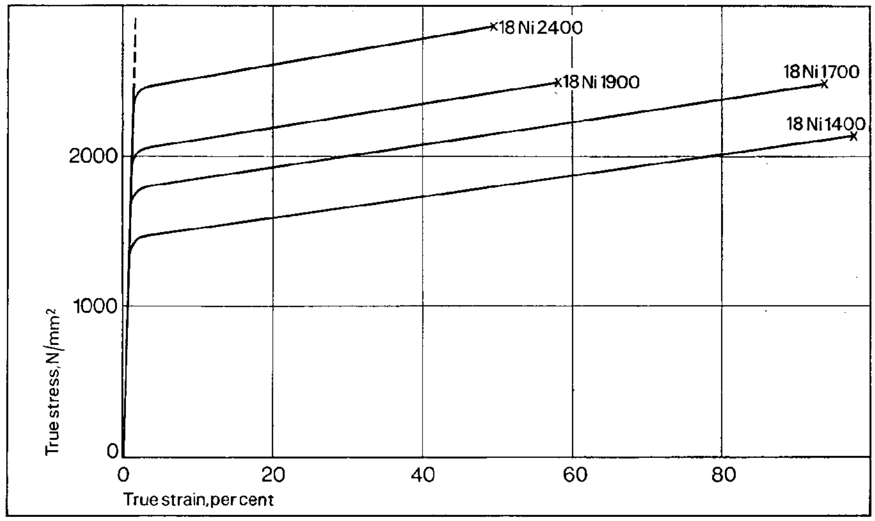

Figure 3. *True stress-true strain curves of maraged steels.*

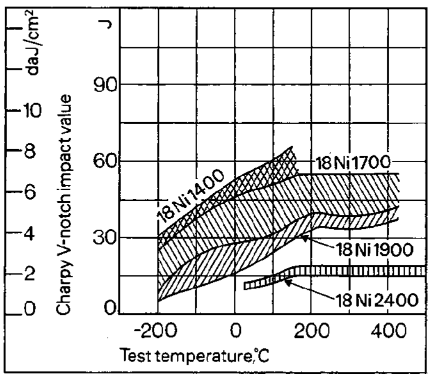

Figure 4. *Charpy V-notch impact value of 18% nickel maraging steels as a function of test temperature.*

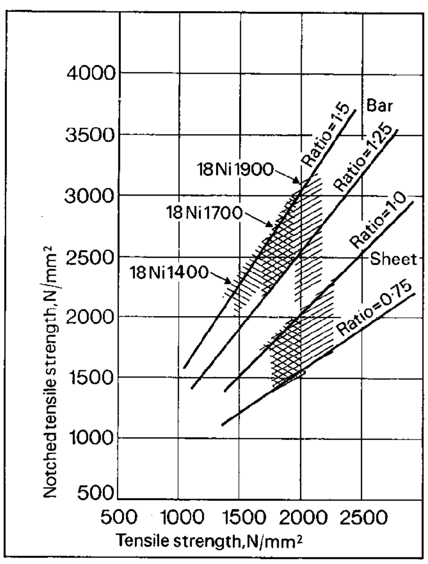

Figure 5. *Notched tensile/tensile strength ratios of maraging steels in bar and sheet form.*

Table 10. *Typical mechanical properties of double vacuum melted 18Ni1900 maraging steel.*
(Solution-annealed and aged 3h 480°C, except as stated otherwise)

Section Size	Direction of test	0.2% proof stress N/mm^2	Tensile Strength N/mm^2	Elong. Lo = $5.65\sqrt{So}$ %	R of A %	Izod impact value J
200mm dia.	Transv.	1930	2030	4	25	9.5
125mm dia.	Transv.	1930	2020	4	20	11
115mm dia.	Transv.	2080	2140	6	25	16
280 × 100mm	Transv.	1910	1970	5	25	–
250 × 57mm *	Transv.	1970	2000	8	35	–
190 × 38mm	Transv.	2020	2120	4	25	13.5
200 × 19mm	Transv.	2020	2140	6	35	16
70 × 70mm	Transv.	1970	2020	4	25	–
83mm dia. × 44mm thick	Tangential	1970	2020	9	50	16
280 × 100mm	Longit.	1950	2010	10	45	–
60 × 60mm	Longit.	2000	2040	8	55	–
19mm dia.	Longit.	2010	2170	8	50	27

** Aged 3h 500°C. (Data by courtesy of Firth Brown Limited, Sheffield, U.K.)*

Table 11. *Typical mechanical properties of double vacuum melted 18Ni2400 maraging steel.*
(Solution-annealed 1h 820°C air cooled, and aged 6h 500°C)

Section Size	Direction of test	0.2% proof stress N/mm^2	Tensile Strength N/mm^2	Elong. Lo = $5.65\sqrt{So}$ %	R of A %	Charpy V-notch impact value	
						J	daJ/cm^2
250 × 250mm	Longit.	2390	2470	6	31	5	0.6
250mm dia.	Longit.	2390	2490	5	24	–	–
105 × 105mm	Longit.	2380	2440	7	34	8	1.0
55 × 55mm	Longit.	2410	2490	8	54	14	1.8
20mm dia.	Longit.	2390	2490	8	51	11	1.4
Tube	Longit.	2390	2470	6	40	7	0.9
150mm dia.	Transv.	2290	2390	3	17	8	1.0
105 × 105mm	Transv.	2410	2470	4	19	5	0.6
55 × 55mm	Transv.	2390	2470	6	34	11	1.4
100 × 25mm	Transv.	2380	2460	4	34	5	0.6

(Data by courtesy of Firth Brown Limited. Sheffield, U.K.)

temperatures is unique at the high strength levels of the maraging steels.

The 18Ni2400 steel exhibits somewhat lower ratios of NTS/UTS than the lower-strength grades as shown in Figure 6.

Fracture mechanics

Metallic components with limited toughness can support tensile loads up to the yield stress if they are sufficiently flawless. Cracks or harmful discontinuities of sufficient size must pre-exist, or develop, for unstable fracture to occur at a stress below the tensile yield (0.2 per cent proof) stress. Fracture mechanics provides a means of determining the quantitative relationship between crack size, the elastic stress field surrounding the crack and the fracture properties of the material.

The controlling parameter in representing the combined effect of crack dimensions and stress field at the leading edge of a crack is K, the stress field intensity. In crack propagation, as the stress increases, the crack will first grow to a critical size determined by the toughness of the material before rapid crack propagation or unstable fracture is initiated. The stress intensity factor at the onset of rapid crack propagation is taken as a measure of fracture toughness and is designated K_c, the 'plane stress fracture toughness'.

Under conditions where the material is relatively ductile, K_c is the controlling factor in determining toughness and a shear type of fracture is obtained. For a given material, K_c varies with thickness and temperature. K_c tends toward a minimum value as the thickness increases and temperature decreases. This minimum value is called the 'plane strain fracture toughness', K_{1c}, and is associated with a brittle mode of rapid crack propagation.

The value of K_{1c} is of great practical importance in evaluating the toughness of high-strength materials. When the stress intensity factor reaches the value of K_{1c} slow crack growth is followed by rapid crack growth and brittle fracture. Of further practical importance is the use of K_{1c} to calculate the critical dimensions of a crack, or flaw, below which the steel may be used without danger of the crack initiating catastrophic failure. Thus it is useful in determining an allowable design stress to prevent propagation of the minimum flaw detectible by inspection.

Representative K_{1c} values of commercial heats of 18Ni1700,1900 and 2400 maraging steels in the solution-treated and aged condition are presented in Table 12. Similar data for cold-rolled and aged sheet of 18Ni2400 are given in Table 13.

Typical K_{1c} values for weldments in 18 per cent Ni maraging steels are given in a later section.

Table 12. *Representative plane strain fracture toughness values (K_{1c}) of double vacuum melted commercial heats of 18Ni1700, 18Ni1900 and 18Ni2400 maraging steels.*
(3-point bend tests on 127mm × 25mm × 12.7mm specimens)

Material	Product section size	Direction of test	Tensile strength	K_{1c}
			N/mm²	MNm $^{-3}/_2$
18Ni1700	127 × 127mm 127 × 127mm 200 × 200mm 250 × 250mm	Longit. Transv. Transv. Transv.	1820 1800 1845 1860	101.5 93.1 89.9 89.8
18Ni1900	130 × 19mm 130 × 19mm	Longit. Transv.	2020 2020	68.7 66.5
18Ni2400	105 × 105mm	Longit.	2440	33

(Data by courtesy of Firth Brown Limited, Sheffield. U.K.)

Table 13. *Plane strain fracture toughness values (K_{1c}) of 18Ni2400 maraging steel sheet, cold rolled and aged 3h 480°C.*
(Transverse tensile tests)

Sheet thickness mm	Cold rolling reduction in thickness %	0.2% proof stress N/mm²	Tensile Strength N/mm²	Elong. %	K_{1c} MNm $^{-3}/_2$
3.7	25	2540	2570	2.5	64
3.0	45	2510–2570	2530–2610	3	58
2.0	60	2590	2600	2	59
1.24	75	2700	2740–2790	2	54

Fatigue properties

Conflicting data from fatigue tests on maraging steels have been reported. This is largely attributable to variations in the procedures used for the production of the test-pieces. The conventional preparation generally applied to high-strength alloy steels, of machining and polishing test-pieces from fully heat-treated material, has sometimes been used, while in other instances the finished test-pieces have been prepared from solution-annealed maraging steel with ageing applied as the final operation. Thus wide ranges of fatigue properties have been obtained. Examples of the effects of test-piece preparation are shown by the fatigue curves in Figures 7–11. These curves also show the effects of notch stress concentration factor and of testing method, viz., rotating bend, tension-tension, and tension-zero stress on given heats of maraging steel. Figures 12–16 summarize comprehensive data on the effects of these factors based on tests of many heats.

The highest fatigue 5 strengths are obtained in shot-peened material of high purity and, where fatigue is an important criterion, the use of vacuum-refined material and application of shot peening to the finished component is recommended.

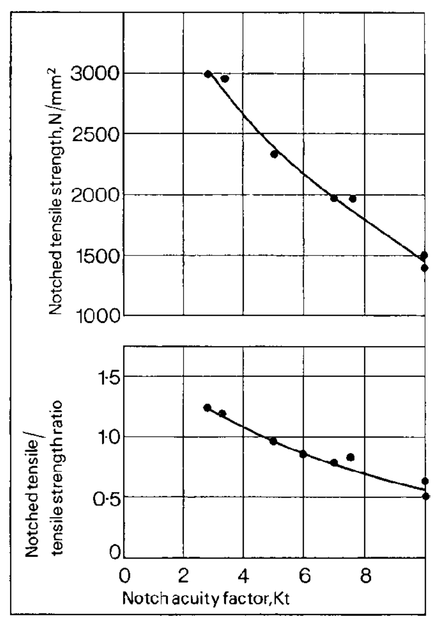

Figure 6. *Variation of notched tensile strength of 18Ni2400 maraging steel and notched tensile/tensile strength ratio, with notch acuity factor, K_t.*

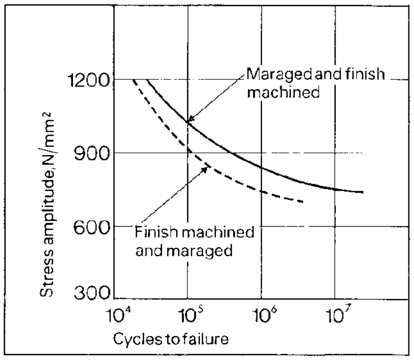

Figure 7. *Smooth-bar rotating-beam fatigue curves of 18Ni400 maraging steel.*

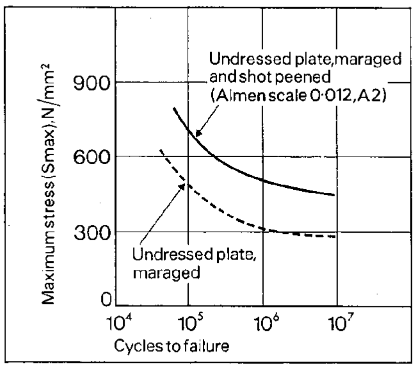

Figure 8. *Tension-zero stress*

$$(R = \frac{S\,min.}{S\,max.} = 0)$$

fatigue curves of 18Ni400 managing steel plate, 5mm thick.

(After Brine F. E., Webber D. and Baron H. G., British Welding Jnl., *1968.* ***15****, (11), 541-546)*

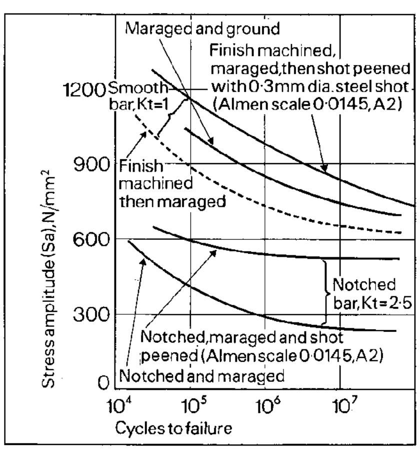

Figure 9. *Notched- and smooth-bar rotating-beam fatigue curves of 18Ni700 managing steel. (K_t = Notch stress concentration factor)*

(Data supplied by W.M. Imrie, Dowty Rotol Limited, Gloucester, U.K.)

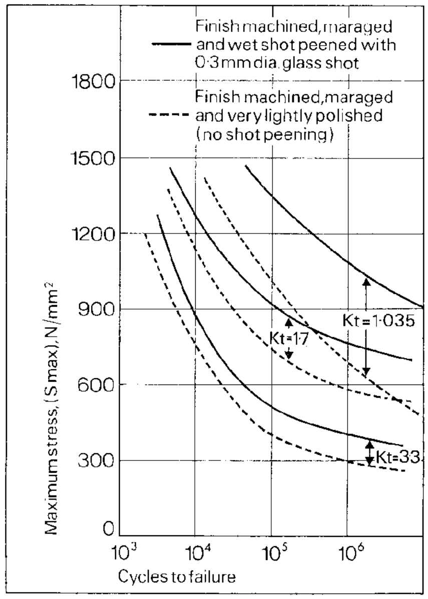

Figure 10. *Tension – tension*

$$(R = \frac{S\,min.}{S\,max.} = 0.1)\ notched\ –$$

bar fatigue curves of 18Ni1700 managing steel. (K_t= Notch stress concentration factor)

(After Souffrant M. P. 'Perspectives d'utilisation du managing en grosses pieces forgees', Conference on Les Aciers Speciaux au Service de l'Aviation, June 1967, Aéroport du Bourget)

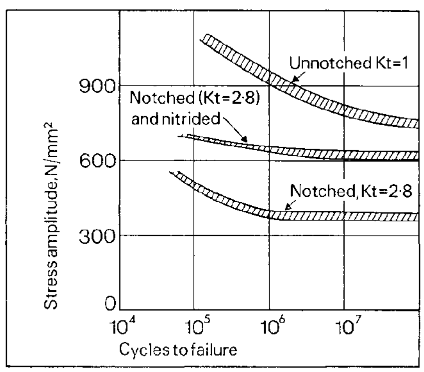

Figure 11. *Rotating-beam fatigue curves of 18Ni2400 managing steel. Nitriding the surface of managing steels improves the resistance to fatigue.*

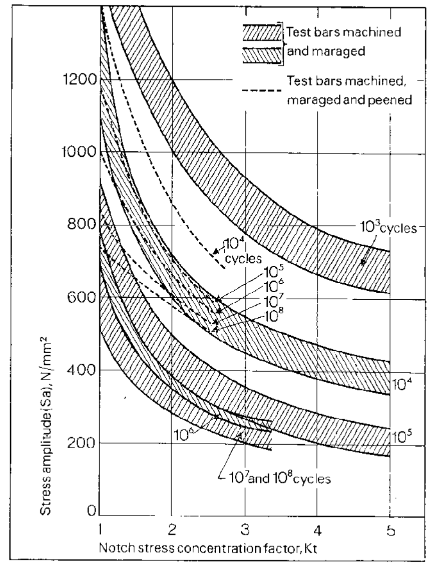

Figure 12. *Effect of notch stress concentration factor on the fatigue strengths of 18Ni1700 and 18Ni1900 managing steels for various cycles to failure.*

$$R = \frac{Smean - Sa}{Smean + Sa} = -1$$

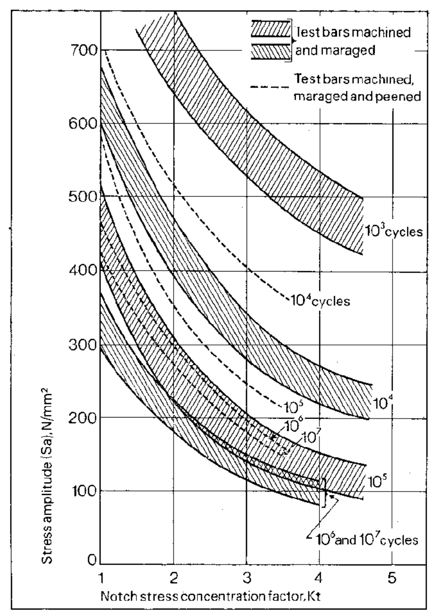

Figure 13. *Effect of notch stress concentration factor on the fatigue strengths of 18Ni1700 and 18Ni1900 maraging steels for various cycles to failure.*

$$R = \frac{Smean - Sa}{Smean + Sa} = 0\ to\ 0.1$$

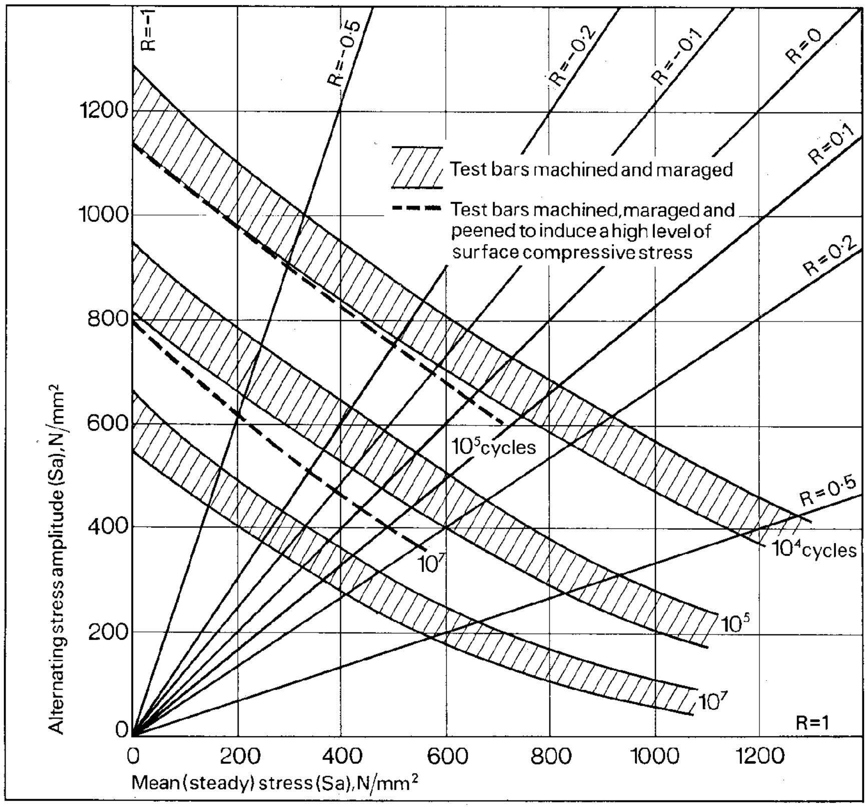

Figure 14. *Fatigue strengths of 18Ni1700 and 18Ni1900 maraging steels for various cycles to failure in smooth-bar tests, K_t =1.0, under alternating stress + steady stress conditions,* $R = \frac{Sm - Sa}{Sm + Sa}$

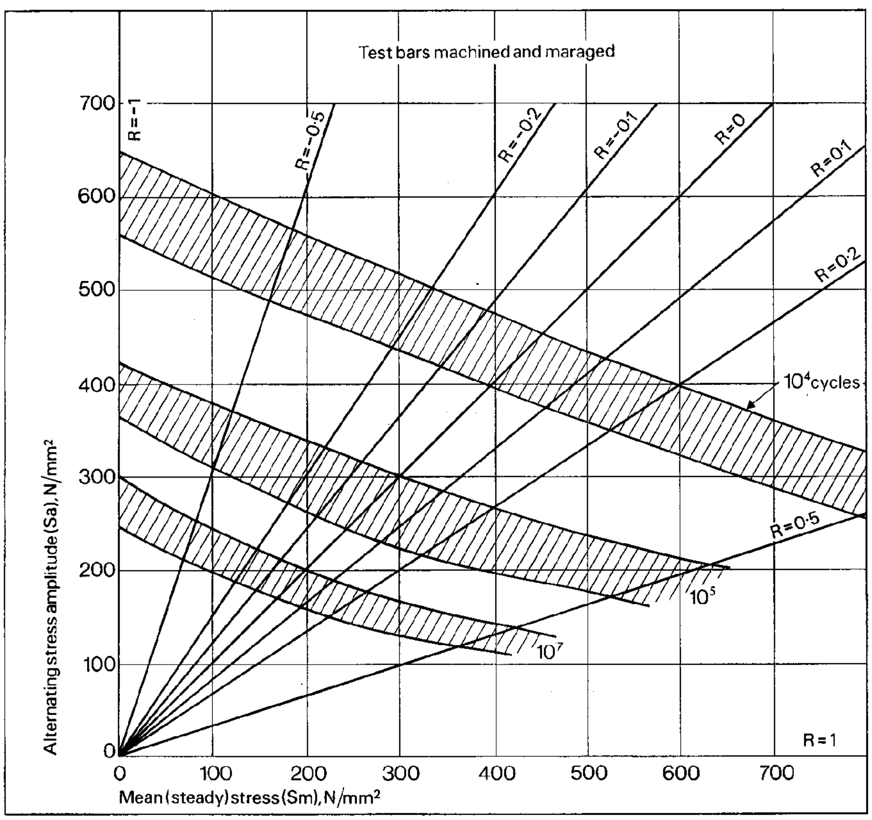

Figure 15. *Fatigue strengths of 18Ni1700 and 1900 maraging steels for various cycles to failure in notched-bar tests, notch stress concentration factor K_t = 2.4–2.5, under alternating stress + steady stress conditions,*

$$R = \frac{Sm - Sa}{Sm + Sa}$$

Properties at elevated temperatures

The effects of temperature on the mechanical properties of the various grades of maraging steel are presented in Figures 17–22 and in Tables 14 and 15.

The dynamic modulus of elasticity values for the 18Ni1400 grade tend to be on the low side of the band shown in Figure 18 and those for the higher strength grades at the high side of that band. The vertical line at 20°C in Figure 18 shows the variation in modulus of elasticity according to the direction of testing in 4 mm thick plate which has been cold rolled 60 per cent followed by ageing. The modulus increases from about 180 to 213 GN/m^2 as the angle to the rolling direction is varied between 0° and 90°. This variation indicates that some preferred crystal orientation exists in the plate. In most applications it is not expected to be of engineering significance.

The effects of long-time exposure at elevated temperatures on tensile and impact properties are shown in Tables 16 and 17 (*page 16*), while stress-rupture and creep properties are presented in Figure 23 (*page 17*) as a Larson-Miller plot. The latter is based on limited data currently available and should be considered as tentative.

Mechanical properties of cast maraging steel (17Ni1600)

The cast grade of nickel maraging steel is normally solution annealed by homogenizing for 4 hours at 1I50°C, followed by air cooling. Maraging of the solution-annealed material is effected by heating for 3 hours at 480°C. Typical mechanical properties after these treatments are presented in Table 18 (*page 16*). That table also shows that use of a double solution-annealing treatment at 1150°C and 820°C, with an intermediate reheating at 595°C, provides a significant improvement in toughness without impairment of tensile properties. Solution annealing at 820°C without prior homogenizing generally results in appreciable loss of ductility.

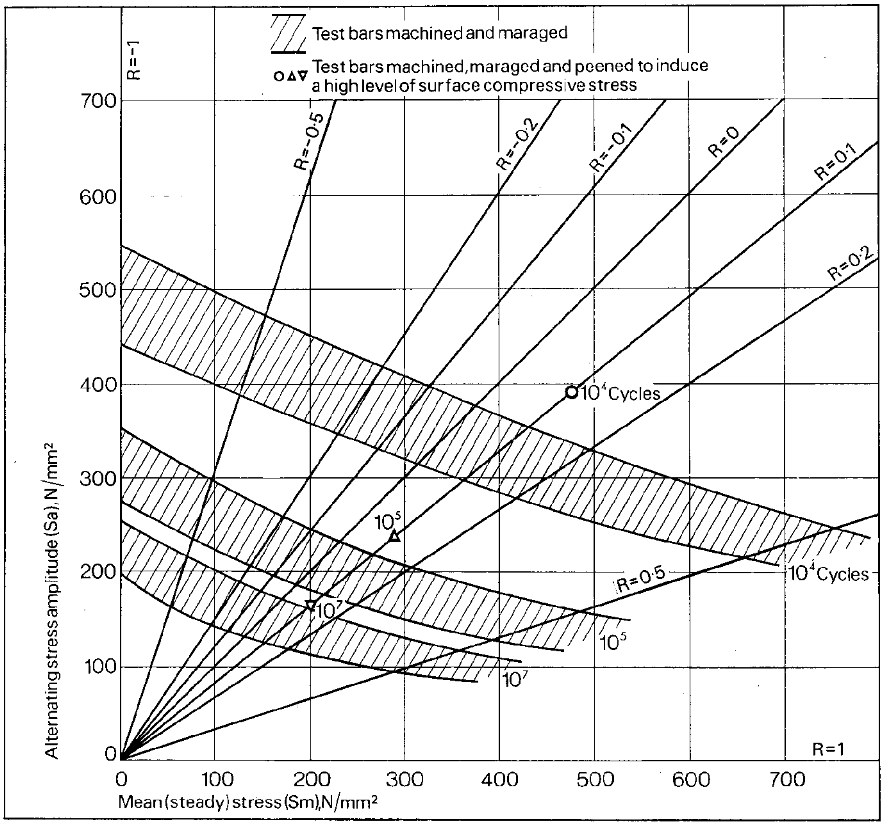

Figure 16. *Fatigue strengths of 18Ni1700 and 1900 maraging steels for various cycles to failure in notched-bar tests, notch stress concentration factor K_t = 3.2–3.3, under alternating stress + steady stress conditions,*

$$R = \frac{Sm - Sa}{Sm + Sa}$$

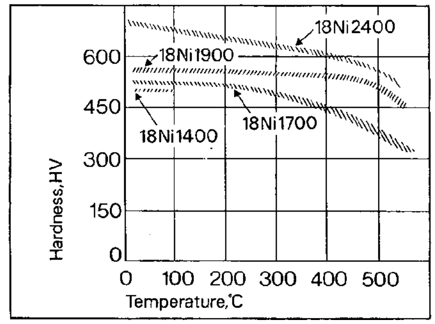

Figure 17. *Hardness of maraging steels as a function of temperature.*

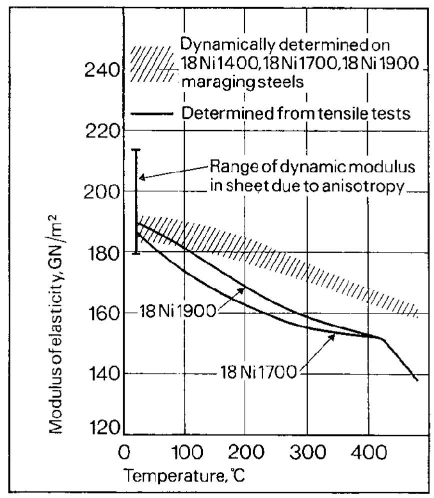

Figure 18. *Effect of temperature on the modulus of elasticity of maraging steels, determined dynamically and by tensile measurements (the variation in the room-temperature dynamic modulus of cold-rolled and aged sheet as a function of angle to the rolling direction is indicated by the range of values shown).*

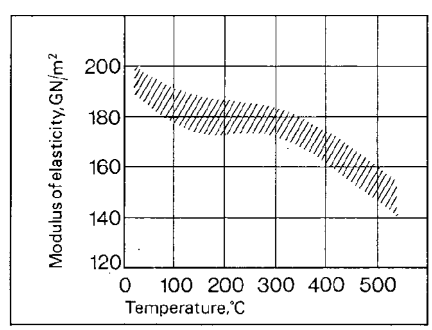

Figure 19. *Effect of temperature on the modulus of elasticity of 18Ni1700 maraging steel in compression.*

Table 14. *Effect of temperature on 0.2 per cent proof stress and tensile strength of 18 per cent nickel maraging steels.*

Test temperature °C	Approximate ratio of strength at test temperature to strength at 20°C	Change in 0.2% proof stress and tensile strength between 20°C and test temperature	
		18Ni1700 and 18Ni1900 grades N/mm²	18Ni2400 grade N/mm²
–100	1.11	+170/250	–
– 40	1.03	+50/80	–
20	1.00	0	0
100	0.95	– 80/140	–140
200	0.90	–160/220	–240
300	0.87	–170/280	–350
400	0.82	–280/420	–440
480	0.73	–420/550	–570

Table 15. *Effect of temperature on compressive yield stress and shear strength of 18 per cent nickel maraging steels.*

Test temperature °C	18Ni1700		18Ni1900			
	Compressive yield stress		Compressive yield stress		Ultimate shear stress	
	N/mm²	Per cent of value at 25°C	N/mm²	Per cent of value at 20°C	N/mm²	Percent of value at 20°C
20	–	–	1980	100	1130	100
25	1840	100	–	–	–	–
150	1650	90	–	–	–	–
175	–	–	1790	90	–	–
315	1540	84	–	–	–	–
345	–	–	1670	84	940	83
430	1450	79	1590	80	860	76
540	1170	76	–	–	–	–

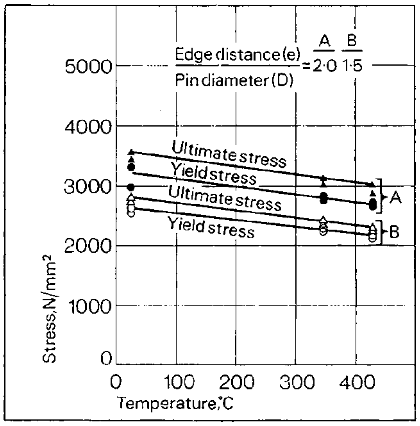

Figure 20. *The bearing strength (ASTM.E238 test) of 18Ni1900 maraging steel as a function of temperature.*

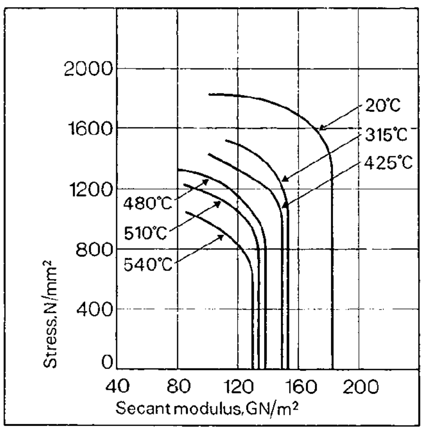

Figure 21. *The secant modulus of 18Ni1700 maraging steel as a function of applied stress at various temperatures. (Data derived from static tests)*

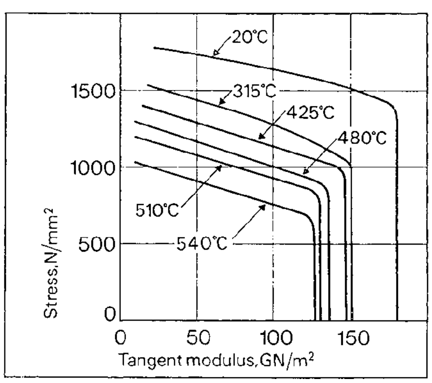

Figure 22. *The tangent modulus vs. stress for 18Ni1700 maraging steel at various temperatures. (Data derived from static tests)*

Table 16. *Effect of long-time exposure at elevated temperatures on room-temperature 0.2 per cent proof stress of 18 per cent nickel maraging steels.*

Condition	0.2% proof stress			
	18Ni1400	18Ni1700		18Ni1900
	N/mm^2	Steel 1 N/mm^2	Steel 2 N/mm^2	N/mm^2
As-maraged	1450	1730	1860	2000
Maraged+200h 150°C	–	1710	–	–
Maraged+200h 260°C	–	1730	–	–
Maraged+200h 370°C	–	1730	–	–
Maraged+200h 480°C	–	1140	–	–
Maraged+200h 540°C	–	830	–	–
Maraged+200h 650°C	–	280	–	–
Maraged+1000h 315°C	1540	–	1950	2060
Maraged+1000h 370°C	1590	–	2000	2180

Table 17. *Effect of long-time exposure at elevated temperatures on room-temperature impact strength of 18 per cent nickel maraging steels.*

Condition	Charpy V-notch impact value					
	18Ni1400		18Ni1700		18Ni1900	
	J	daJ/cm^2	J	daJ/cm^2	J	daJ/cm^2
As-maraged	56	7.0	24	3.0	18	2.3
Maraged+1000h 315°C	43	5.4	22	2.8	18	2.3
Maraged+1000h 370°C	52	6.5	16	2.0	18	2.3

Table 18. *Typical mechanical properties of cast 17Ni1600 maraging steel.*

Heat treatment: a – Homogenized 4h 1150°C, air cooled.
b – 4h 1150°C + 4h 595°C + 1h 820°C, air cooled.
c – 4h 1150°C + 3h 480°C.
d – 4h 1150°C + 4h 595°C + 1h 820°C + 3h 480°C.

Property	Solution annealed		Maraged			
	a	b	c		d	
0.2% proof stress. N/mm^2	740	750	1650			
Tensile strength. N/mm^2	960	990	1730			
Elongation, Lo=5.65$\sqrt{So}$.%	12	13	7			
Reduction of area, %	58	62	35			
Notched/smooth tensile strength ratio	–	–	1.25			
Modulus of elasticity(E). GN/m^2	–	–	188			
Modulus of rigidity (G) (torsional) GN/m^2	–	–	72			
Poissons ratio	–	–	0.30			
Hardness: HV	295	320	530			
HRC	29	32	49			
Plane strain fracture toughness (K_{1c}). $MNm^{-3/2}$	–	–	82.5			
Charpy V- notch impact value at:			J	daJ/cm^2	J	daJ/cm^2
–196°C	–	–	3	0.38	8	1.0
–100°C	–	–	9	1.1	18	2.3
–40°C	–	–	16	2.0	20	2.5
20°C	–	–	18	2.3	22	2.8

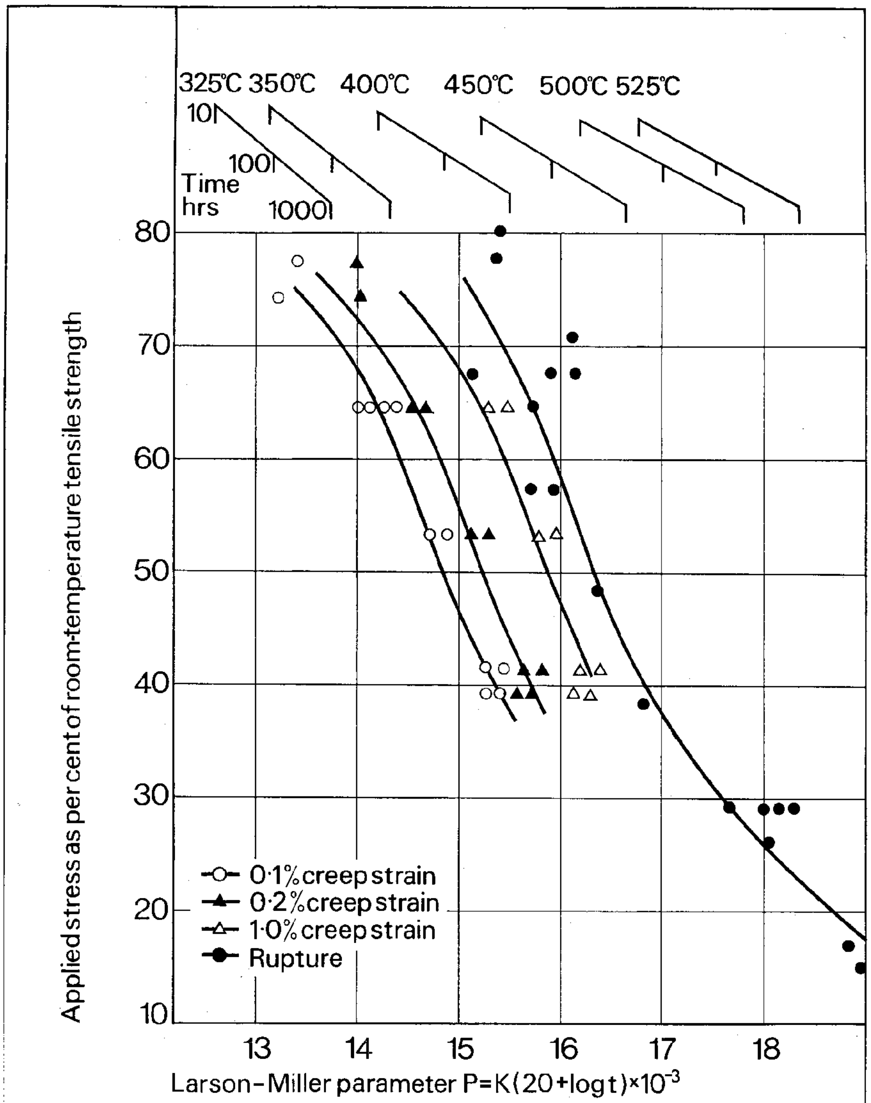

Figure 23. *Larson-Miller plot of creep- and rupture-strength of 18% nickel maraging steels. The plotting of applied stress as per cent of the room-temperature tensile strength normalizes the data for all grades. The time-temperature conversion scales along the top of the diagram enable the LarsonMiller parameter to be converted into time and temperature values.*
K = Absolute temperature (Kelvin)   t = Time in hours

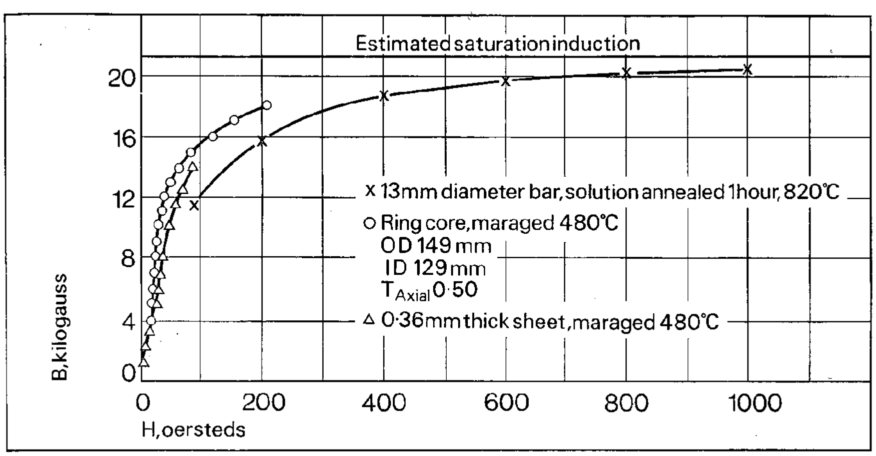

Figure 24. *D.C. magnetization curves of 18Ni1700 maraging steel in the solution-annealed and the maraged conditions. Normal coercive force values (Hc) of 18Ni1700 are: Solution-annealed 22–34 oersteds, 1750–2700 A/m. Maraged 21–54 oersteds, 1670–4300 A/m.*
Approximate remanence (Br) = 5.5 kilogauss or 0.55 teslas.

Physical properties

These are presented in Table 19 (*page 18*) and Figure 24.

Processing and forming

Hot working

The maraging steels are readily hot worked by conventional rolling and forging operations. A preliminary soak at 1260°C may be used for homogenization, except, for the 18Ni2400 grade for which soaking in the range 1200–1230°C has been found to be more satisfactory. If the latter steel is inadvertently soaked at 1260°C or higher, it is necessary to hold for a time at the lower suggested temperature to eliminate any possible damage that may have been caused by the high-temperature exposure. For all grades adequate working should be applied to break up the as-cast structure and minimize directionality. For optimum properties a minimum reheating temperature of 1100°C should be used prior to final hot working. Hot working can continue to 870°C for 18Ni2400 and to 820°C for the lower-strength grades. A fine grain size is obtained by application of adequate reductions at the lower temperatures during final hot working and this enhances toughness. The transverse ductility and toughness of thick sections receiving only limited amounts of hot work may be reduced compared with thinner material, this effect being partly attributable to an embrittling reaction which can occur in the prior austenite grain boundaries if the steels are cooled slowly through the critical temperature range 980–760°C. The mechanical properties of material embrittled by this mechanism can be restored by reheating to 1200°C and cooling rapidly to room temperature.

Examples of the effects of hot-work finishing temperature and of variation in cooling rate after hot working are shown in Figures 25–30 (*pages 18–19*). For the 13mm plate represented in these diagrams, finishing temperature and mode of cooling had no marked effect on the tensile properties after solution annealing and ageing (Figures 26 and 27). On the other hand, fracture toughness (K_{1c}) measurements on fatigue-precracked edge-notched bend specimens showed greater effects of finishing temperature and cooling rate (Figures 28-30), illustrating that relatively rapid cooling is desirable from any finishing temperature and that the need for rapid cooling is greater for the higher finishing temperatures. If rapid cooling cannot be achieved (e.g., if air-cool ing must be used), a low finishing temperature with significant reduction at that temperature is desirable.

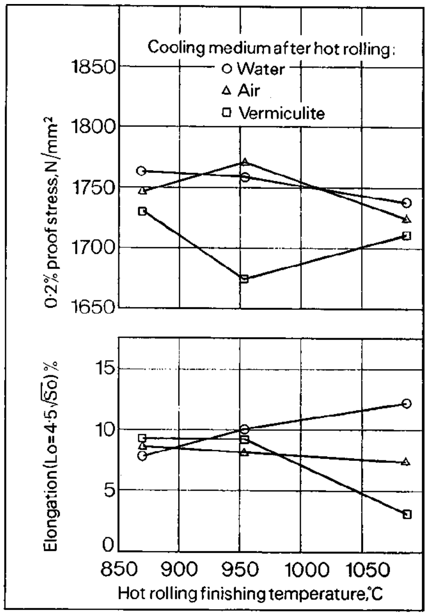

Figure 25. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on the tensile properties of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: hot-rolled and aged.

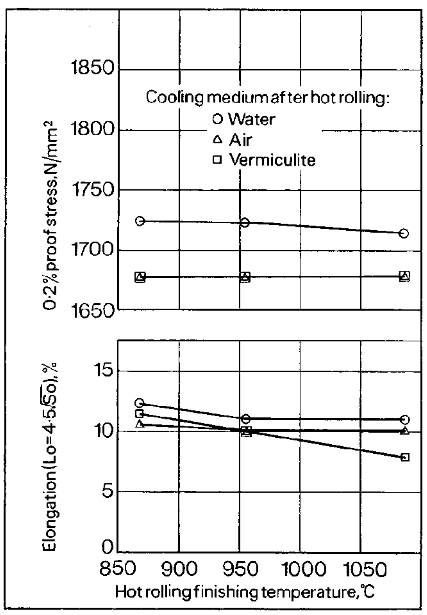

Figure 26. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on the tensile properties of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: annealed at 815°C and aged.

Table 19. *Physical properties of nickel-cobalt-molybdenum maraging steels.*

Property	Wrought grades				Cast grade	
	18Ni1400, 18Ni1700, 18Ni1900		18Ni2400		17Ni1600	
Density g/cm³	8.0		8.1		8.0	
Specific heat	KJ/kgK	cal/g°C	kJ/kgK	cal/g°C	kJ/kgK	cal/g°C
	0.46	0.11	0.46	0.11	0.46	0.11
Thermal	W/mk	cal/cms°C	W/mK	cal/cms°C	W/mK	cal/cms°
conductivity at: 20°C	21	0.050	–	–	29	0.070
100°C	23	0.054	–	–	32	0.077
200°C	26	0.061	–	–	37	0.088
300°C	27	0.064	–	–	–	–
400°C	28	0.066	–	–	41	0.099
480°C	28	0.067	–	–	–	–
Mean coefficient of thermal expansion 10^{-6}/K						
20–100°C	9.9		–		9.6	
20–200°C	10.2		–		10.0	
20–300°C	10.6		–		10.5	
20–400°C	11.0		–		10.8	
20–480°C	11.3		11.4		11.0	
Linear contraction on ageing, % approx.	18Ni 1400: 0.04; 18Ni 1700: 0.06; 18Ni 1900: 0.08		0.09		0.03	
Electrical resistivity, * μ Ω cm:	18Ni1700					
Solution annealed 820°C	60–70		–		–	
Maraged 3h 480°C	35–50		–		–	

** The electrical resistivity increases within the ranges given primarily with the titanium content of the steel.*

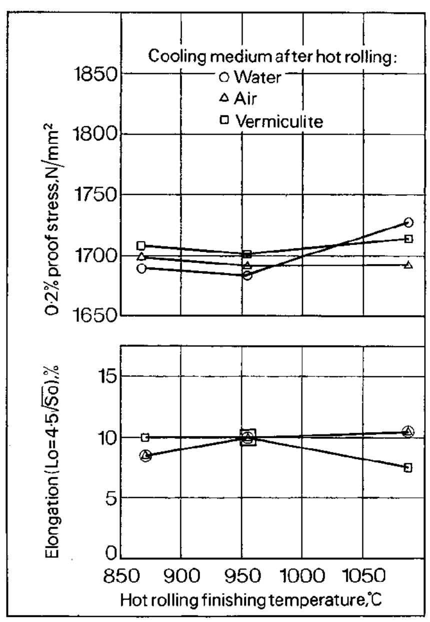

Figure 27. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on the tensile properties of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: annealed at 870°C and aged.

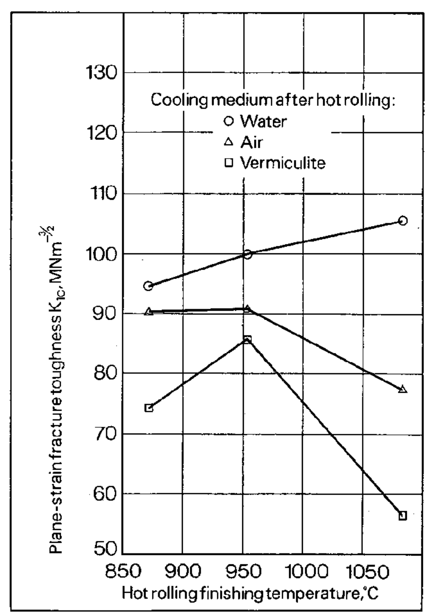

Figure 28. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on plane-strain fracture toughness (K_{1C}) of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: hot-rolled and aged.

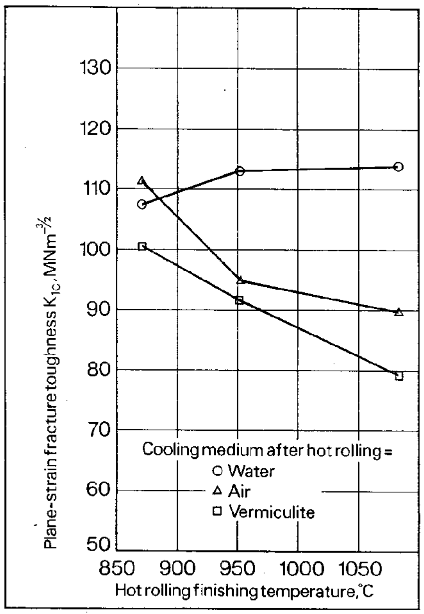

Figure 29. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on plane-strain fracture toughness (K_{1c}) of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: annealed at 815°C and aged.

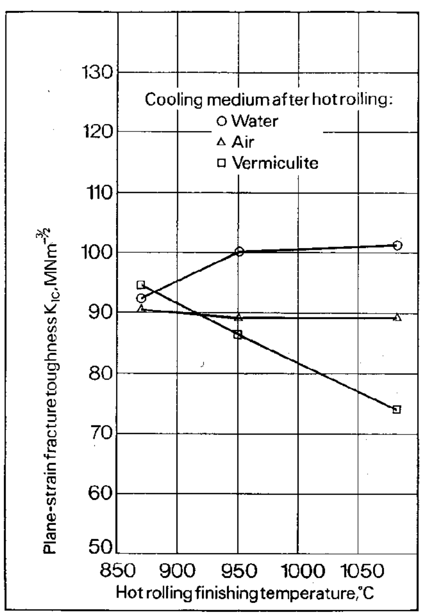

Figure 30. *Effect of hot-rolling finishing temperature and subsequent mode of cooling on plane-strain fracture toughness (K_{1c}) of 18Ni1700 maraging steel plate (13mm thick, 35% reduction in final pass at finishing temperature).*
Condition: annealed at 870°C and aged.

Cold working

Hot-rolled or annealed maraging steels are easily cold worked. They work-harden very slowly and can be reduced substantially (up to 85 percent reduction) before intermediate annealing is required (Figure 31). The low work-hardening rate facilitates production of sheet, strip and wire. For forming and drawing applications, cold-rolled solution-annealed material is preferred because of its relative freedom from surface irregularities. However, hot-rolled solution-annealed material with good surface quality has performed satisfactorily. Tube spinning, shear forming, deep drawing, hydroforming, heading of fasteners, bending and shearing can all be accomplished by cold processes.

Cold work prior to ageing can be used to increase strength after maraging. Figures 32–34 show the change in the 0.2 per cent proof stress as a function of per cent cold reduction in 18Ni1700, 18Ni1900 and 18Ni2400. In all cases the proof stress for a given ageing treatment increases at an approximately constant rate up to about 50 per cent reduction, but thereafter strength increases at a higher rate for the 18Ni2400 steel, whereas for the lower-strength steels there is no further gain in strength with increase of cold work above 50 per cent and in some instances the strength may fall below the peak value corresponding to about 50 per cent reduction. Ductility also declines in maraged material above about 40 per cent reduction and when maximum toughness is required in the end product, it is desirable to limit cold reduction to 40 per cent.

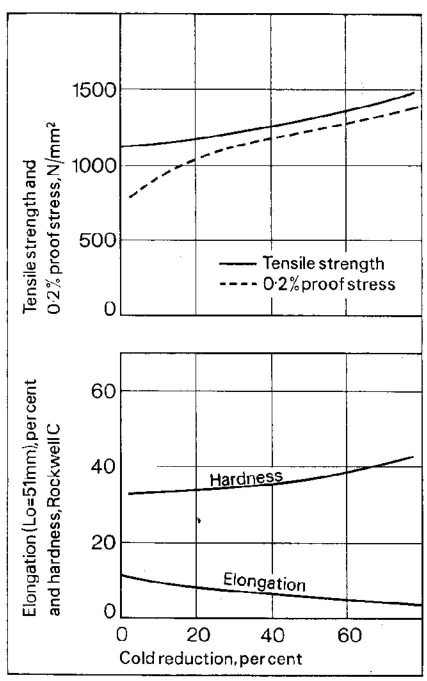

Figure 31. *Effect of cold work on the tensile properties and hardness of solution-annealed maraging steel.*

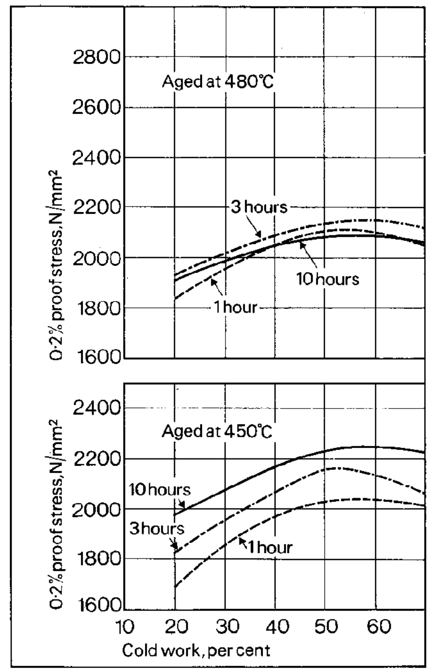

Figure 32. *The 0.2% proof stress of 18Ni1700 maraging steel is improved by cold working prior to ageing at 450°C and 480°C.*

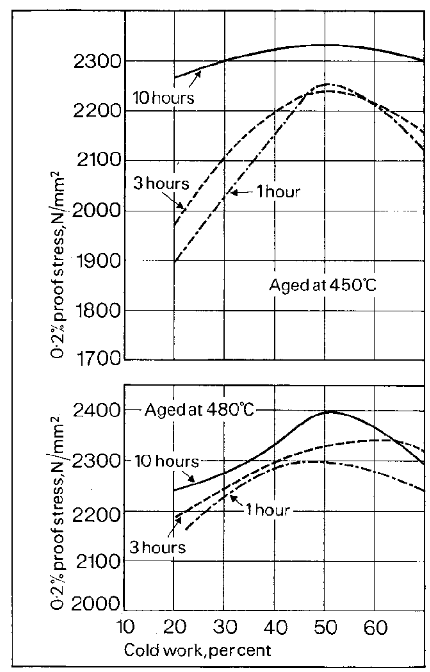

Figure 33. *Effect of cold work prior to ageing at 450°C and 480°C on the 0.2% proof stress of 18Ni1900 maraging steel.*

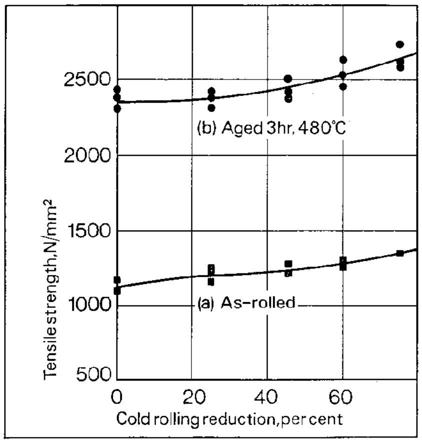

Figure 34. *Tensile strength of 18Ni2400 maraging steel sheer (a) annealed and cold rolled, (b) annealed, cold rolled and aged.*

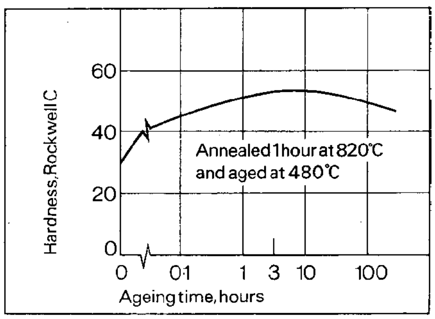

Figure 35. *Typical age-hardening curve of maraging steels. The hardening response is initially very rapid, while at the optimum ageing temperature the effect of overageing is slight even after 200 hours.*

Heat treatment

The simple heat treatment cycle of the maraging steels is one of the major advantages of these materials. The alloys are normally solution-annealed at 820°C for a minimum time of 15–30 minutes for 1.3 mm thick sections and for one hour per 25 mm for heavier sections, followed by air cooling to room temperature. Air cooling is an adequate quenching rate to induce complete transformation to martensite throughout the heaviest sections because at temperatures above the martensite formation range the austenite has high stability and does not transform to other decomposition products such as ferrite, peralite or bainite, even at relatively slow cooling rates.

Solution-annealing at 820°C is generally sufficient to give complete recrystallization of hot-worked structures and to ensure the formation of a fully-austenitic structure from which martensite can form on cooling, whereas heating below that temperature may not achieve these requirements for the attainment of optimum strength and toughness. However, with some heats and product forms of the 18Ni1400, 1700 and 1900 grades heating above 820°C may be

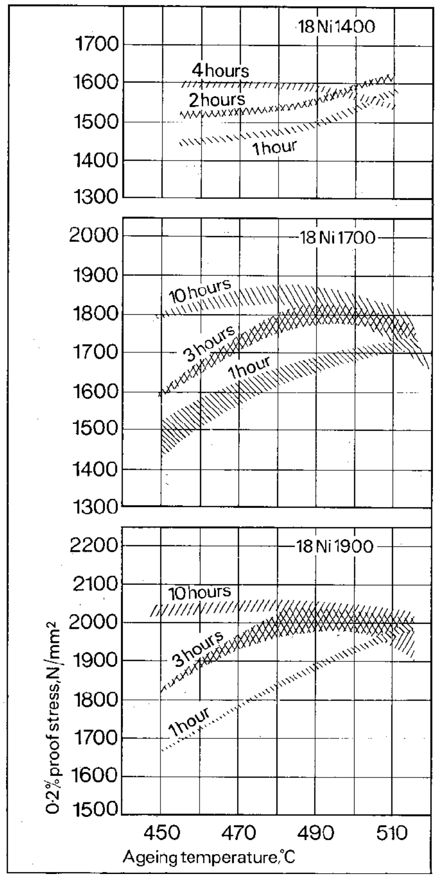

Figure 36. *Effect of ageing temperature and time on the 0.2% proof stress of maraging steels.*

necessary to promote recrystallization in order to obtain optimum transverse properties. On the other hand, increasing the annealing temperature above 820°C for the 18Ni2400 grade causes a gradual but definite drop in all properties.

The high strength properties of the 18Ni1400, 1700, 1900 and cast 17Ni1600 maraging steels are developed within relatively short time when the annealed steels are aged at 480°C, the standard ageing time being 3 hours, while the effect of overageing is slight even after 200 hours (Figure 35). The 18Ni2400 steel age-hardens at somewhat slower rate and an ageing temperature between 480°C and 540°C for times up to 12 hours at 480°C, or shorter times at the higher temperatures, is suggested to achieve the nominal 0.2 per cent proof stress of 2400 N/mm^2. Ageing this higher-strength steel at 510°C for 3 hours usually gives the optimum strength and toughness.

The effects of variations in maraging temperature and time on mechanical properties are presented in Figures 36–39.

Special furnace atmospheres to prevent decarburization during heat treatment are not required because of the low carbon content of the maraging steels. Normal precautions to prevent carburization, sulphurization or excessive oxidation are required. Fuel low in sulphur is preferred for fuel-fired furnaces. Fuel oil containing not more than 0.75 per cent (w/w) sulphur is satisfactory and fuel gas should contain no more than 2.3 grams of total sulphur per cubic metre (l grain/cubic foot). All carbonaceous- and sulphur-containing impurities should be removed from the surfaces of material before annealing. Direct flame impingement on work material should be avoided. To produce a surface free of oxide, the material is heated and cooled to room

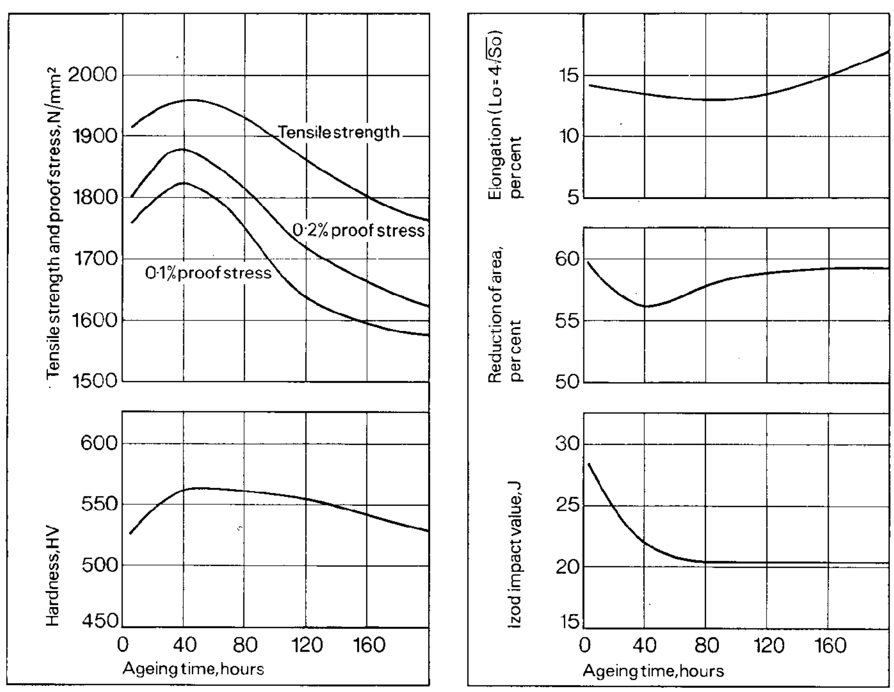

Figure 37. *Effect of ageing time at 480°C on the mechanical properties of 18Ni1700 maraging steel.*
(Data by courtesy of Firth Brown Limited, Sheffield, U.K.).

temperature in an atmosphere of either pure dry hydrogen with a dew point of –43°C or dissociated (completely dissociated) ammonia with a dew point of –45° to –50°C.

A variant of the normal maraging heat treatment may be applied to finished products of the 18Ni2400 steel to provide additional hardening. This involves cooling the material slowly from 820°C or higher, or interrupting the cooling cycle in the temperature range 510–650°C and holding for several hours prior to cooling to room temperature. Ageing of the austenitic matrix occurs, 'Ausaging', which may be due to precipitation of the eta phase (Ni_3Ti). Subsequent maraging then increases the hardness to 61–62 Rc compared with about 58 Rc for normally annealed and maraged material. The hardening response induced by interrupted cooling from 820°C is shown in Figure 40.

The ausaging reaction can also occur during cooling after hot working, but generally it should be avoided at that stage by ensuring that there are no delays in cooling through the temperature range 650-510°C, since it may impair subsequent processing (e.g., cold working and machining) and might cause unsuspected and non-uniform properties in hot-rolled or heavy sections. An anneal of one hour at 820°C is usually sufficient to eliminate this effect.

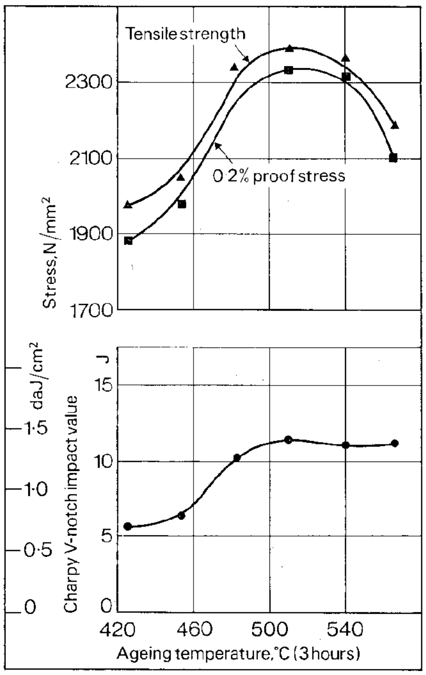

Figure 38. *Variation of tensile and impact properties of 18Ni2400 maraging steel with ageing temperature (steel annealed 1h 820°C before ageing).*

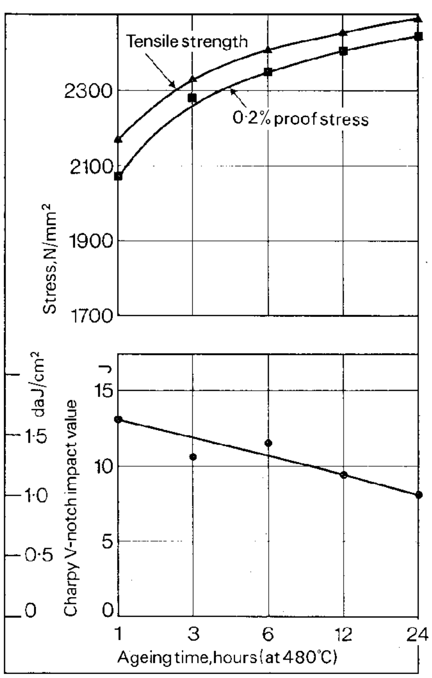

Figure 39. *Variation of tensile and impact properties of 18Ni2400 managing steel with ageing time (steel annealed 1h 820°C before ageing).*

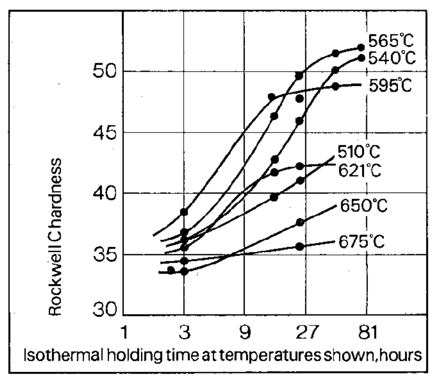

Figure 40. *Hardening induced in 18Ni2400 managing steel by interrupted cooling (Ausaging) from 820°C. Subsequent ageing (Managing) gives further hardening.*

A further heat treatment variant may he applied to 18Ni2400 steel in the processing of ultra-high-strength wire to produce the best combination of strength and toughness at a given strength level. Instead of applying an intermediate anneal at the normal temperature of 820°C, between wire drawing steps, the material is annealed for 1 hour at 620°C. This results in partial reversion of the low-carbon martensite to austenite with retention of the latter phase on cooling to room temperature. Subsequent working creates instability of the austenite and, after final maraging, maximum strength is developed combined with improved ductility. These effects on properties are shown by the data given in Table 20 which compares material given intermediate annealing at both 820°C and 620°C.

Dimensional stability

The nature of the maraging hardening mechanism is such that close dimensional control can be maintained in components that are finish-machined in the soft, annealed, condition and subsequently hardened. Absence of retained austenite also ensures that the alloys will be free of further dimensional change in service. During maraging a very small uniform contraction occurs; the percentage changes for the various wrought grades of steel are shown in Figure 41. As illustrated by the curves for the 18Ni2400 steel, overageing by heating at higher temperatures or longer times than those normally used for maraging may result in higher-than-normal shrinkage and should be avoided in finished products made to close tolerances.

Table 20. *Effects of intermediate annealing on the mechanical properties of 18Ni2400 wire.*

Drawing procedure:			
Pre-drawing annealing treatment	1h 815°C	1h 815°C	1h 815°C
Initial diameter, mm	6.4	6.4	5.8
First reduction, %	87	87	85
Size, mm	2.3	2.3	2.3
Intermediate anneal or reversion heat treatment	1h 815°C	1h 627°C	1h 627°C
Final reduction, %	87	87	87
Final size, mm	0.8	0.8	0.8
Tensile properties of as-drawn wire:			
0.2% proof stress, N/mm^2	1260	1990	2030
Tensile strength, N/mm^2	1540	2530	2540
Elongation, %	0.86	1.2	1.7
Tensile properties of drawn and aged wire:			
0.2% proof stress, N/mm^2	–	2530	2600
Tensile strength, N/mm^2	2710	2960	2960
Elongation, %	–	1.2	0.9

Nitriding

Maraging steels can be simultaneously nitrided and aged at 430–480°C to provide a shallow but hard case to improve wear resistance and/or fatigue properties. At the lower nitriding temperatures, 430–450°C, a surface hardness of about 860 HV can be obtained with a total case depth of about 0.15 mm after 48 hours' treatment. A typical hardness traverse through a nitrided case is shown in Figure 42. Nitriding above 450°C produces some stable austenite in the nitrided zone and decreases the hardness. However, at 480°C a hardness of about 800 HV can still be achieved and the total case depth may be increased to about 0.25 mm after 70–90 hours' treatment.

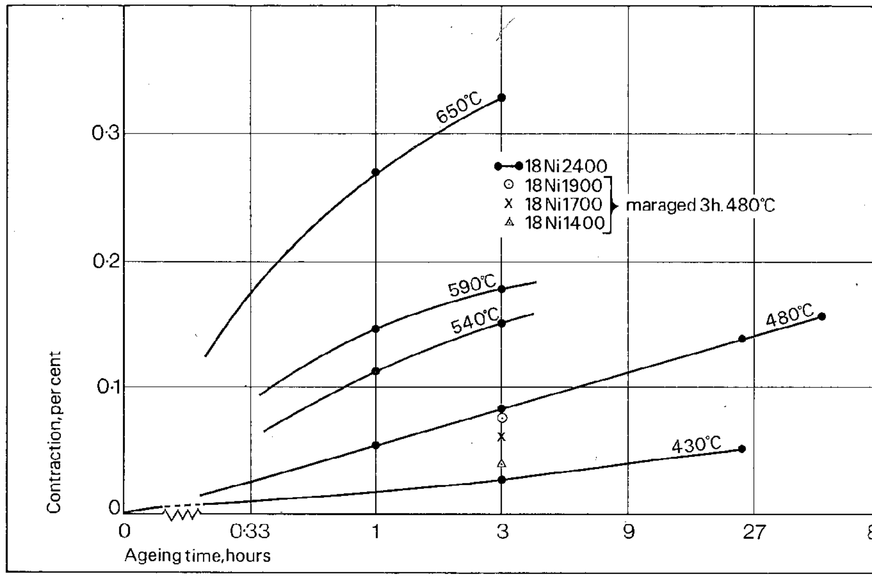

Figure 41. *Dimensional changes, due to ageing or ageing and reversion, of 18Ni2400 maraging steel aged at various temperatures, and of the lower-strength wrought grades given the standard maraging treatment at 480°C. The steels were initially annealed one hour at 820°C.*

Welding and joining

Nickel maraging steels are readily weldable without preheat in either the solution-annealed or fully-aged conditions. Gas-shielded arc processes are preferred; considerable experience and confidence has been generated with the TIG process. A machined groove preparation is desirable and the joint design may be the same as is commonly used for carbon steels. An argon gas shield is recommended for TIG and MIG welding, while pure helium is recommended for MIG short-arc welding. The maximum interpass temperature should be 120°C. Thorough interpass cleaning by power wire brushing is recommended. No postheat is required, but a post-weld ageing treatment such as 3 hours at 480°C is used to strengthen the weld and the heat-affected zone.

Heat-affected zone

The behaviour of the heat-affected zone of maraging steels contributes to their good welding characteristics. There is no cracking problem as in conventional high-strength low-alloy steels, and very little distortion occurs whether welding maraging steel in the solution-annealed or aged condition. The hardness distribution in the HAZ of solution-annealed material is shown in Figure 43. After welding, very little softening occurs in the parent metal and the joint has virtually the same strength as the annealed parent material. Following post-weld ageing, negligible variation in hardness is observed in the heat-affected zone.

The HAZ hardness distribution of maraging steel welded after ageing is shown in Figure 44. Softening may be observed. in the grain-coarsened area near the fusion line and in regions which experience peak temperatures of approximately 650°C where partial austenite reversion and stabilization occurs. Tests of welded joints show that the fracture occurs in the weld metal, and that the characteristic notch toughness of the

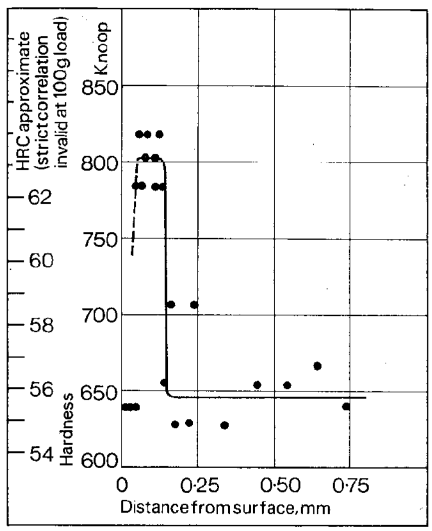

Figure 42. *Hardness of nitrided case on 18Ni2400 maraging steel billet, 95mm diameter. Steel annealed one hour 820°C, then simultaneously aged and nitrided 48 hours at 450°C in 25-30% dissociated ammonia (Knoop hardness determined with 100 gram load).*

base metal is retained in the heat-affected zone. After re-ageing the weld area, virtually uniform hardness is obtained in the weld zone.

Gas-shielded processes

An essentially matching composition filler wire is used to weld the 18Ni1700 grade and has also been used for welding 18Ni1400 and 18Ni1900. Vacuum-melting and vacuum-annealing of the wire product is used in production of the filler material to provide the low impurity and hydrogen levels (H_2 is typically < 5 ppm) required for maximum weld properties. Filler wire

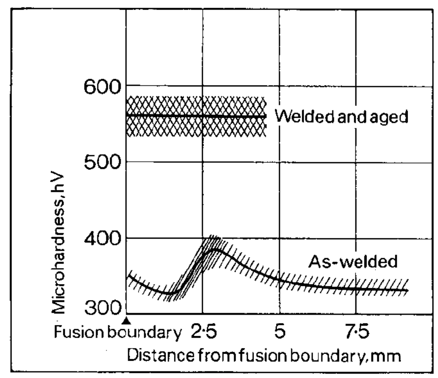

Figure 43. *Typical heat-affected-zone hardness distribution in maraging steels welded in the solution-annealed condition. As-welded and after subsequent ageing.*

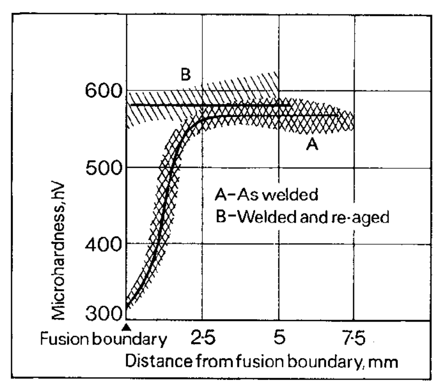

Figure 44. *Typical heat-affected- zone hardness distribution in maraging steels welded in the aged condition. As-welded and after subsequent re-ageing.*

compositions closely matching these of the parent metals have also been developed for welding the 18Ni1400, 18Ni1900 and 18Ni2400 maraging steels. However, most work has been done with the 18Ni1400 and 18Ni1700 grades. Typical wire compositions are shown in Table 21.

Heat inputs are maintained as low as possible to achieve optimum strength and toughness in the weld deposits and rather low travel speeds are employed to avoid contamination of the weld metal by atmospheric gases. Typical welding parameters are shown in Table 22.

Representative mechanical properties of TIG, MIG and short-circuiting arc weldments are presented in Table 23. The fracture toughness measurements of welded maraging steels are lower than those of the parent material but are better than those of conventional quenched and tempered steels at the same proof stress levels. Joint efficiencies of 95–100 per cent are usual in welds of maraging steels having nominal proof stress values of up to 1700 N/mm^2, but welds made with high heat inputs can have efficiencies down to 85 per cent and occasionally may be lower. Tensile failures in such welds often occur in the heat-affected zone as the result of formation of relatively large amounts of stable austenite. As the strength of the parent material is raised above 1700 N/mm^2 proof stress, joint efficiencies decrease. Small beads and low input help to keep strength reductions to a minimum. Solution-annealing a weld prior to ageing can increase strength significantly, but this may often be impractical.

The toughness of TIG weld-deposits is generally superior to that of MIG weld-deposits made either by spray or short-circuiting techniques.

Flux-coated electrode welding

Electrodes for manual metal-arc welding the 18Ni1400 and 1700 maraging steels have been developed, but have not been

Table 21. *Typical weld filler wire compositions.*

Grade	Composition. Weight per cent					
	Ni	Co	Mo	Ti	Al	Other
18Ni1400	18.2	7.7	3.5	0.24	0.10	0.03 max. C 0.01 max. S 0.01 max. P 0.10 max. Si 0.10 max. Mn < 50ppm O < 50ppm N < 5ppm H Bal Fe
18Ni1700	18.1	8.0	4.5	0.46	0.10	
18Ni1900	17.9	9.9	4.5	0.80	0.12	
18Ni2400	17.4	12.4	3.7	1.6	0.17	

Table 22. *Typical parameters for gas-shielded arc welding.*

Process	Volts	Amps	Travel speed mm/min.	Wire diameter mm	Wire feed rate m/min.	Shielding gas dm^3/h
TIG	11–15	200–240	100–180	1.6	0.5–0.76	Argon 850
MIG	28–30	280–300	250	1.6	5	Argon 1400
Short Arc	24	140	Manual	0.8	–	He 1400

Table 23. *Representative mechanical properties of gas-shielded arc weldments. (Welds aged 3h 480°C, except as stated otherwise)*

Material welded	Thickness(a)	Fillet wire type and source	Welding process	0.2% proof stress	Tensile strength	Elong. Lo=25mm	Red. of area	Charpy V-notch impact value		K_{1c}
				N/mm^2	N/mm^2	%	%	J	daJ/cm^2	$MNm^{-3/2}$
18Ni1400	Plate	18Ni1400(C)	TIG	1370	1430	13	60	47	5.9	–
		18Ni1400(C)	MIG	1430	1480	6	34	28	3.5	–
		18Ni1700(L)	MIG	1380	1480	7	30	24	3.0	–
		18Ni1700(C)	TIG	–	1690(bd)	–	–	–	–	122
		18Ni1700(C)	MIG	–	1670(bd)	–	–	–	–	78
		18Ni1700(C)	Short Arc	–	1690(bd)	–	–	–	–	67
18Ni1700	Plate	18Ni1700(C)	MIG	1560	1670	4	7	14	1.8	–
		18Ni1700(C)	MIG	1610	1660	6	2.8	–	–	–
		18Ni1700(C)	MIG	–	1650(bd)	–	–	–	–	82
		18Ni1700(C)	TIG	–	1720(bd)	–	–	–	–	92
		18Ni1700(C)	Short Arc	–	1720(bd)	–	–	–	–	77
		18Ni1700(C)	TIG	1800	1850(d)	4	–	–	–	–
		18Ni1700(C)	TIG	1790(f)	1850(d)	3	–	–	–	–
		18Ni1700(L)	Short Arc	1570	1690	4	14	16	2.0	–
		18Ni1700(L)	MIG(e)	1660	1680	6	21	–	–	–
		18Ni1700(L)	MIG(e)	1520	1620	7	30	19	2.4	–
	Sheet	18Ni1700(L)	TIG	1690	1700	–	–	–	–	210 (Kc)
18Ni1900	Plate	18Ni1700(L)	MIG	1660	1680	6	21	–	–	–
		18Ni1900	TIG	1390	1680	8	40	–	–	65
		18Ni1900	MIG	1600	1690	3	13	–	–	59
	Sheet	18Ni1900	TIG	1800–1930	1830–1970	–	–	–	–	124–178 (Kc)
		18Ni1900	TIG	1650	1670	3 (on 51 mm)	–	–	–	–
18Ni2400	Sheet	18Ni2400	TIG	1970	2030	1.5 (on 51 mm)	–	–	–	36

(a) Plate = 10–25 mm thick.
Sheet = 1.5–2.5 mm thick.
(b) Converted from Vickers Hardness value.
(d) Welds aged 4h 490°C
(e) All weld metal properties.
(f) Weld locally aged.
(C) Commercially produced.
(L) Laboratory produced.

used commercially to any great extent. Core wire compositions are basically the same as those of the parent alloys, except that the titanium contents are increased to allow for high losses of this element across the arc. However, under normal fabrication conditions the titanium losses are variable and unpredictable.

In studies of MMA welding there has been no real difficulty in achieving welds of the required high strength, but they have been associated with a greater propensity to weld cracking and poorer toughness than has been observed in joints made by inert-gas welding.

Submerged-arc and electroslag welding

Both processes provide good joint strength, but weld ductility and toughness are low. In addition, multipass welds in submerged-arc welds have been subject to cracking. Neither of these processes is currently recommended for welding 18 per cent Ni maraging steels where maximum weld properties are required.

Other joining methods

Limited work on conventional spot- and seam-welding has shown promise, but more work is needed before these processes can be recommended for maraging steels. Ageing can be accomplished in the machine, although the relatively high-temperature short-time ageing cycles promote the formation of some austenite.

Excellent friction-welded joints have been achieved. This process is especially useful for joining shafting, tubing and bar products. Table 24 presents typical tensile properties of friction welds.

Flash welding has not been successful to date; low tensile strength and especially low tensile ductility have sometimes been encountered. Additional work on optimizing the welding parameters may overcome this difficulty.

Satisfactory electron-beam welds have been made by a number of fabricators in several thicknesses of maraging steels from thin sheet to moderately thick plate. However, published information to date suggests that it is difficult to make sound welds consistently, particularly in thick plate. Edges to be welded must be machined to close tolerances to ensure the proper fit-up that is an essential part of making good electron-beam welds. A variety of welding conditions that have been used is summarized in Table 25 together with the mechanical properties of the joints obtained. The ductilities, as measured by reduction of area, were generally about half those of the base-plate values.

Dissimilar metal butt joints have been made in 13 mm plate between 18Ni1700 maraging steel, type 304 (18Cr-10Ni) stainless steel, mild steel, HY-80 (2¾ per cent Ni-Cr-Mo) and SAE4340 (1¾ per cent Ni-Cr-Mo) steels. The results showed (Table 26) that sound joints can be produced without difficulty and, as may be expected, the strength of a particular joint is governed by the weaker material of the combination.

Table 24. *Tensile properties of friction welds in 25mm diameter bar of 18Ni1700 maraging steel. (Welds aged 3h 480°C)*

Specimen	0.2% proof stress N/mm^2	Tensile strength N/mm^2	Elong. Lo = 51 mm %	R of A %
Unwelded bar	1760	1810	12	58
Friction weld[(a)]	1730	1790	7	35
Friction weld[(a)]	1730	1780	7.5	36
Friction weld[(a)]	1740	1780	7.5	40
Friction weld[(b)]	1800	1820	7.3	38

(a) 13 mm diameter specimen.
(b) 19 mm diameter specimen.

Table 25. *Mechanical properties of electron-beam welds* [(a)] *in maraging steel plates.*

Grade and thickness of plate	Welding conditions: No. of Passes	Voltage kv	Current mA	Travel speed cm/min.	Heat treatment[(b)]	Mechanical properties: 0.2% proof stress N/mm^2	Tensile strength N/mm^2	Elong[(c)] %	R of A %	Charpy V- notch impact value: J	daJ/cmz	K_{1c} $MNm^{-3/2}$
18Ni1700 2.5mm		Unwelded	–	–	SA	1760	1830	5.7	28	–	–	–
	1	30	65	100	SAW	1140	1140	2.5	21	–	–	–
		30	65	100	SAWA	1870	1890	4.1	13	–	–	–
		30	65	100	SWSA	1780	1820	3.2	13	–	–	–
18Ni1700 7.5mm		Unwelded	–	–	SA	1820	1840	15	–	–	–	–
	1	150	20	150	SAW	1670	1670	4	–	–	–	–
		150	20	150	SAWA	1810	1830	4	–	–	–	–
		150	20	150	SWSA	1880	1900	5	–	–	–	–
18Ni1700 13mm		Unwelded	–	–	SA	1710	1790	22	51	–	–	–
	1	150	17	43	SAW	1250	1300	8	30	–	–	–
		150	17	43	SAWA	1720	1800	14	25	–	–	–
18Ni1700 25mm		Unwelded	–	–	SA	1740	1790	12	50	–	–	96
	1	50	320	100	SAWA	1770	1790	4	28	–	–	75
		50	320	100	SWSA	1760	1770	6.5	41	–	–	{80, 94}
18Ni1400 25mm		Unwelded	–	–	SA	1430	1480	23	56	–	–	–
	1	50	400	100	SAW	1010	1040	7	31	19 (defects)	2.4	–
		50	400	100	SAWA	1350	1370	4	13	27	3.4	–
18Ni1400 25mm		150	13	25	SAW	1100	1160	10	32	–	–	–
	2	150	13	25	SAWA	1460	1500	7	14	–	–	–

(a) All samples failed in the weld.
(b) S = Solution-annealed. A = Aged. W = Welded.
(c) The tensile elongations must be treated with caution since the weld metal sometimes constitutes only a small portion of the gauge length.

Brazing has been successfully accomplished using palladium-containing and silver-copper-zinc alloys. Brazing temperatures in the range 800–870°C are considered to be the most suitable since temperatures in the austenite reversion range should be avoided unless the component is to be re-solution-treated prior to final ageing, while at temperatures above 870°C, times should be restricted to avoid grain coarsening and loss of ductility and toughness in the steel. For furnace brazing high vacuum is satisfactory, while dry hydrogen or argon atmospheres can also be used successfully providing a flux or pre-plated (e.g., with iron) surfaces are employed to achieve good flow and braze coverage. For torch brazing, use of a flux is mandatory, whether or not a pre-plate is used, although the latter does improve braze coverage and strength.

The degree of overlap in single-lap brazed shear specimens has a marked effect on shear strength, as shown in Figures 45 and 46, with strength decreasing rapidly as the overlap is increased. This is characteristic of brazements, because as the overlap increases, the greatest part of the load is carried by the ends of the joint while the central portion carries little load. In spite of the decrease in specific shear stress the tensile strength of the joint increases as the overlap increases (see Figures 45 and 46).

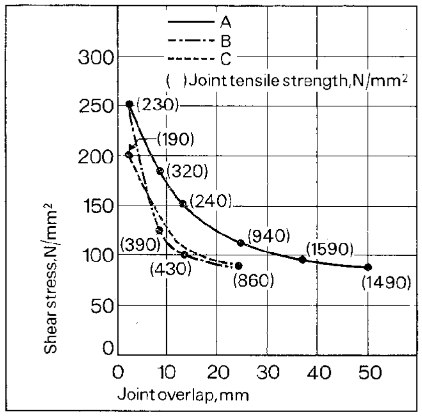

Figure 45. *Effect of degree of overlap on shear strength of single-lap furnace-brazed joints in maraging steels. Specimens aged 3 hours 480°C after brazing.*
A – 68% Ag, 27% Cu, 5% Pd brazing alloy; approximate liquidus temperature 810°C. Specimens brazed in argon.
B – 48% Ni, 31% Mn, 21% Pd brazing alloy; approximate liquidus temperature 1120°C. Specimens brazed in vacuum.
C – 54% Ag, 40% Cu, 5% Zn, 1% Ni brazing alloy; approximate liquidus temperature 855°C. Specimens brazed in argon.

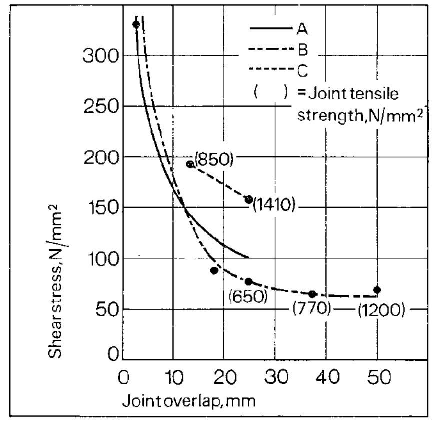

Figure 46. *Shear stress vs. overlap of torch-brazed single-lap joints in maraging steels. Specimens were pre-plated with iron and brazed with use of a flux, then aged 3 hours 480°C.*
A – 82% Cu, 18% Pd brazing alloy; approximate liquidus temperature 1090°C.
B – 53% Cu, 38% Zn, 9% Ag brazing alloy; approximate liquidus temperature 870°C.
C – 27% Cu, 68% Ag, 5% Pd brazing alloy; approximate liquidus temperature 810°C.

Table 26. *Mechanical properties (transverse)* (a) *of 13 mm thick weld joints between 18Ni1700 maraging steel and various dissimilar metals (post-weld heat treatment – 3h 480°C).*

Metal being joined	Filler material	Welding Process	Condition	0.2% proof stress N/mm²	Tensile strength N/mm²	Elong.(a) Lo= 4.5√So %	R of A %	Location of fracture(b)	Charpy V-notch impact value(c) J	Charpy V-notch impact value(c) daJ/cm²
Mild steel	INCO-WELD * 'A'	Manual Arc	As-welded	390	480	16	67	P	108	13.5
			Aged	320	470	16	66	P	133	16.6
HY-80 steel	INCO-WELD * 'A'	Manual Arc	As-welded	380	610	14	43	W	106	13.3
			Aged	400	610	10	29	W	98	12.3
AISI 4340 steel	INCO-WELD * 'A'	Manual Arc	As-welded	390	650	13	45	W	108	13.5
			Aged	420	690	12	34	W	94	11.8
AISI 304 stainless	INCO-WELD * 'A'	Manual Arc	As-welded	350	610	26	34	W	129	16.1
			Aged	370	630	36	79	P	132	16.5
Mild steel	18% Ni maraging steel(d)	MIG	As-welded	430	480	6	65	P	34	4.3
			Aged	340	460	5	65	P	22	2.8
HY-80 steel	18% Ni maraging steel(d)	MIG	As-welded	750	800	8	59	P	30	3.8
			Aged	740	800	7	58	P	14	1.8
AISI 4340 steel	18% Ni maraging steel(d)	MIG	As-welded	1010	1110	4	13	W	22	2.8
			Aged	1170	1240	4	13	P	11	1.4
AISI 304 stainless	18% Ni maraging steel(d)	MIG	As-welded	430	620	23	76	P	38	4.8
			Aged	420	620	32	75	P	19	2.4

Weld Conditions	*Manual Arc*	*MIG*
Current	125 A	280–290 A
Voltage	24 V	32 V
Travel speed	150mm/min.	250mm/min.
Wire feed	Manual	
Heat input	12kJ/cm	20–22kJ/cm
Filler size	4mm rod	1.6mm wire
Preheat	None	None

(a) 6.4 mm diameter tensile bar.
(b) Location of tensile fracture. W = Weld. P = Dissimilar metal being joined.
(c) Notched through weld, axis of notch normal to plane of plate.
(d) Filler composition: 17.9 Ni, 8.1 Co, 4.9 Mo, 0.5 Ti, 0.13 Al, balance essentially Fe.

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Joint clearance, like overlap, affects joint strength: Figure 47 shows that the narrower the gap, the higher the strength. ‘Contact clearance’, i.e., between 0 and 35 µm, provides the best strength, while a gap of about 0-15 mm reduces the strength to about 70 per cent of the maximum level.

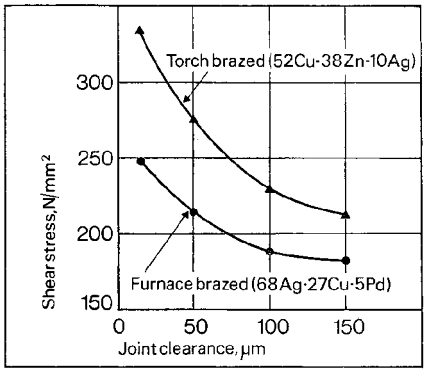

Figure 47. *Average shear stress as a function of joint clearance in brazed maraging steel joints at an overlap of 2.5mm.*

Machining and grinding

Maraging steels are machined most easily in the annealed condition. However, machining of maraged material is also possible and, in general, for either condition the same procedures should be used as are employed for conventional alloy steels having equivalent hardness levels. Rigid equipment and firm tool supports are essential. Tools should receive a copious stream of cutting fluid, with every effort being made to get the lubricant to the tool cutting edge.

Grinding is essentially the same as grinding conventional constructional steels when using a heavy-duty water-soluble grinding fluid as is employed with stainless steels. It is essential to use the heavy-duty grinding fluid as wheel wear is substantially greater with an ordinary water-soluble oil.

Suggested machining procedures are given in Table 27.

Table 27. *Some suggested machining procedures for maraging steels.* (1)

TURNING. Single point and box tools.

Condition of Stock	Tool material	Depth of cut mm	Speed m/min.	Feed mm/rev.	Lubricants* *
Annealed	HSS *, AISI types T15, M33, M41-47	0.64–3.8	21–27	0.13–0.25	2, 5, 7
	Carbide, ISO type K10		107–145	0.18–0.38	0, 4, 6
Maraged	HSS *, AISI types T15, M33, M41-47		14–18	0.13–0.25	3, 5, 7
	Carbide, ISO type K10		32–49	0.13–0.25	0, 4, 6

REAMING

Condition of stock	Tool material		Reamer diameter, mm: 6	113	25	38	51	Speed, m/min.	Lubricants* *
			Feed, mm/rev.						
Annealed	HSS*, AISI types T15, M33, M41–47	0.08	0.13	0.20	0.30	0.38	0.46	17	2, 5, 7
	Carbide, ISO type K20	0.08	0.15	0.20	0.30	0.38	0.46	49	1,4.6
Maraged	HSS*, AISI types T15, M33, M41–47	0.03	0.03	0.03	0.03	0.03	0.03	3	3
	Carbide, ISO type K20							15	2.3

DRILLING

Condition of stock	Tool material	Nominal hole diameter, mm: 3	6	13	19	25	38	51	Speed m/min.	Lubricants* *
		Feed, mm/rev.								
Annealed	HSS*, AISI types T15, M33, M41–47	0.08	0.13	0.18	0.23	0.25	0.33	0.38	17	2, 5, 7
Maraged		0.05	0.08	0.10	0.10	0.10	0.10	0.10	6	3

TAPPING

Condition of stock	Tool material	Speed m/min.	Lubricants* *
Annealed	HSS*, AISI types M10, M7, M1	6	3, 5, 7
Maraged	HSS, nitrided M10, M7, M1	1.5	3

1) *Machining data are largely reproduced from the ‘Machining Data Handbook’ of the Machinability Data Center, Metcut Research Associates Inc., U.S A.. with their kind permission.*

* *HSS - High Speed Steel*
** *Lubricants: 0 Dry.*
1 Light duty oils (general purpose).
2 Medium duty oils (sulphurized or chlorinated).
3 Heavy duty oils (sulphurized or chlorinated) .
4 Soluble oils (light duty).
5 Soluble oils (heavy duty).
6 Synthetic (light duty. general purpose).
7 Synthetic (heavy duty).

SAWING (Annealed stock)					
Circular sawing. Tool material HSS* AISI types M2, M7	Thickness or bar diameter, mm				Lubricants* *
	6–76	76–150	150–230	230–380	
Pitch, mm	5.1–16.5	15.2–24.1	22.9–29.2	27.9–39.4	3, 5, 7
Cutting speed, m/min.	14	12	11	8	
Feed, mm/rev.	50–100	38–76	25–50	19–38	
Power hacksawing HSS* blade	Material thickness, mm				Lubricants* *
	< 6	6-20	20-50	> 50	
Teeth/dm	40 or more	40	24	16	2, 5, 7
Speed, strokes/min.	85	85	85	85	
Feed, mm/stroke	0.13	0.13	0.13	0.13	

PLANING									
Condition of stock	Tool material	Cutting speed m/min.	Feed, mm			Depth of cut, mm		Lubricants* *
			Rough planing	Finish planing	Parting	Rough planing	Finish planing	
Annealed	Tungsten or molybdenum HSS*	12–15	0.4	5 max.	0.2 max.	5	0.25	0 for rough planing, 2 or 3 for finish planing and parting
Maraged		7.5	0.4	5 max.	0.1 max.	5	0.25	

MILLING							
	Face milling		Slab milling	End milling - peripheral		End milling - slotting	
Tool material for:	HSS* AISI type	Carbide ISO type	HSS* AISI type	HSS* AISI type	Carbide ISO type	HSS* AISI type	Carbide ISO type
Annealed stock	T15, M33, M41–47	K20	T15. M33, M41–47	M2, M7	P20	M2, M7	
Maraged stock				T15, T17, M33, M41–47		–	K10
Depth of cut, mm	0.64–3.8	0.64–3.8	0.64–3.8	0.64–3.8	0.38–1.3	1.3–6.4	1.3–6.4
Speed m/min: Annealed stock	26–34	79–94	20–26	23–29	84–107	18–21	–
Maraged stock	9–12	20–26	–	8–9	23–30	–	12–15
Feed: mm/tooth: Annealed stock	0.08–0.13	0.13–0.15	0.10–0.13	0.03–0.05(a) 0.08–0.10(b)	0.04–0.05(a) 0.10–0.13(b)	0.013(c) 0.05–0.06(d)	–
Maraged stock	0.08–0.13	0.08–0.10	–	0.03(a)(b)	0.03–0.05(a) 0.08–0.10(b)	–	0.03 0.04(d)
Lubricants* *: Annealed stock	2, 5, 7	0, 4, 6	2, 5, 7	2, 5, 7	0, 4, 6	2, 5, 7	0, 4, 6
Maraged stock	3	0, 2	3	3	3	3	3

(a) *Cutter diameter 12.5 mm*
(b) *Cutter diameter 25-51 mm*
(c) *Width of slot 6.4 mm.*
(d) *Width of slot 25-51 mm.*

Descaling and pickling

The oxide on hot-worked or thermally treated materials may be removed by blasting or pickling by the procedures described below. Fused salt-bath pickling processes that operate at or above 320°C should not be used on maraging steels. The mechanical properties may be modified by treatments at or above that temperature.

Duplex pickling

Immerse work in Solution No. 1. The time required for the removal of oxide with a specific chemical pickling solution is dependent upon the nature and the amount of oxide. To avoid over-pickling, the work should be frequently inspected during pickling.

Solution No. 1

	Parts by volume
Water	3
Hydrochloric acid (20° Baumé)	4
Temperature	70°C
Time	20 to 40 min. (additional time might be required for loosening heavy oxide)
Containers	earthenware crocks, glass, ceramic or acid-proof brick-lined vessels

The work coming from Solution No. 1 should be rinsed in cold water and immersed in Solution No. 2. The work from Solution No. 2 should be rinsed in cold water and then neutralized in a 1 to 2 per cent (by volume) ammonia solution.

Solution No. 2

	Parts by volume
Water	14
Nitric Acid (70%)	5
Hydrofluoric Acid (52%)	1
Temperature	25–30°C
Time	1½ to 2 min.
Containers	carbon or brick-lined tank

Single bath pickling procedure

Solution No. 3 is a rapid pickling solution that should be used cautiously to avoid over-pickling. This solution leaves a black smut on the surface of the pickled material. Following pickling the work should be rinsed in cold water and then neutralized in a 1 to 2 per cent (by volume) ammonia solution.

Solution No. 3

	Parts by volume
Water	20
Sulphuric Acid (66° Baumé, 93%) or (60° Baumé, 78%)	 3 4
Temperature	65-75°C
Time	Approx. 15 min. (avoid over-pickling by inspecting the work for time of withdrawal)
Containers	earthenware crocks, glass, or ceramic vessels or rubber-lined tanks

Corrosion characteristics

In atmospheric exposure, unprotected 18 per cent nickel maraging steels corrode in a uniform manner and become rust-covered. Pit depths tend to be more shallow than for conventional low-alloy high-strength steels, while corrosion rates of the maraging steels are about half those of low-alloy steels as shown by the data presented in Figures 48–50.

The corrosion rates for both maraging and low-alloy steels in seawater are similar initially, but from about six months onwards the former corrode more slowly (Figure 51).

In tap water and some neutral salt solutions the maraging steels are susceptible to pitting, but have lower average corrosion rates than low-alloy steels. Similarly the corrosion rates of maraging steels in acid solutions, although substantial, are lower than those of low-alloy steels. In general, protection of maraging steels from corrosive solutions is advisable.

Figure 52 shows that maraging steel has substantially greater resistance to oxidation in air at 540°C than a 5 per cent chromium tool steel.

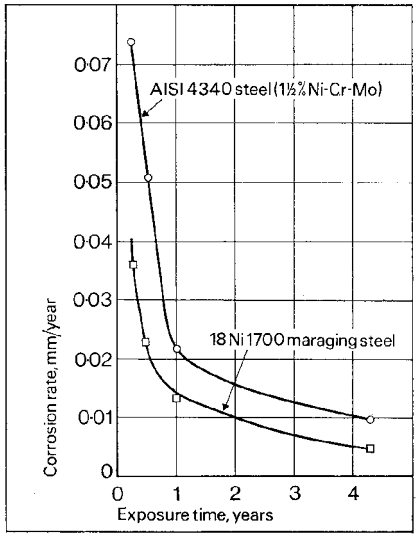

Figure 48. *Corrosion rates of maraging and low-alloy steels in an industrial atmosphere (at Bayonne, New Jersey, U.S.A.).*

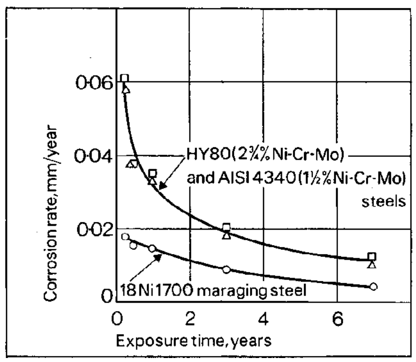

Figure 49. *Corrosion rates of maraging and low-alloy steels, 24 metres from the sea, at Kure Beach, North Carolina, U.S.A.*

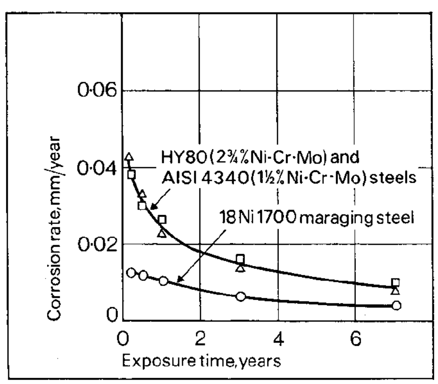

Figure 50. *Corrosion rates of maraging and low-alloy steels, 240 metres from the sea, at Kure Beach, North Carolina, U.S.A.*

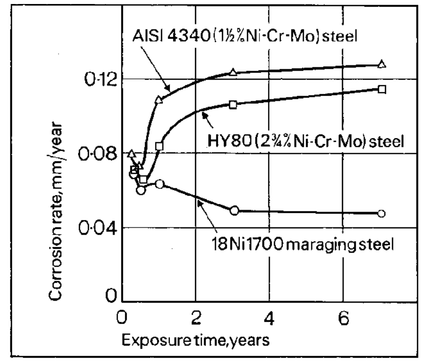

Figure 51. *Corrosion rates of maraging and low-alloy steels in seawater flowing at 0.61 metres per second.*

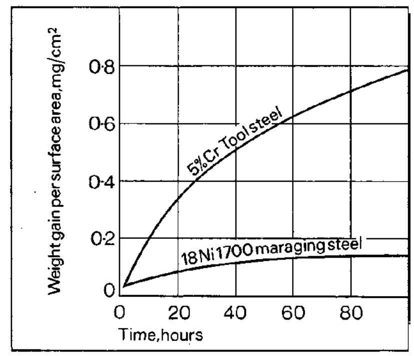

Figure 52. *The oxidation rate at 540°C of 18Ni1700 maraging steel compared with that of 5% chromium steel. Tests performed on 6.4mm cubes in refractory crucibles, exposed to still air for total times of 5, 25 and 100 hours.*

Stress-corrosion characteristics

In an earlier section the measurement of Plane Strain Fracture Toughness, K_{1c}, as an engineering criterion of toughness, has been described. This fracture mechanics approach to engineering design can also be used to measure the resistance of a material to propagation of a pre-existing crack in the presence of a corrosive environment. Thus it is possible to determine the critical stress intensity factor, designated K_{1scc}, below which a crack will not propagate under static loading conditions. Values of K_{1scc} are invariably less than those for K_{1c}.

Figure 53 presents K_{1scc} data for unprotected 18 per cent nickel maraging steels in relation to the 0.2 per cent proof stress, with comparative data for some high-strength low-alloy steels and stainless steels. These data embrace exposure in aqueous environments with and without NaCl, but the variations in environments are not distinguished since there is no distinct difference between their effects on K_{1scc}. Included in Figure 53 are lines showing critical crack depth, a_{cr}. The regions above these lines

correspond to combinations of strength and K_{1scc} which a long crack of the specified depth will not propagate when stressed to the 0.2 per cent proof stress, while the regions below the lines correspond to strength/K_{1scc} combinations for which the crack would propagate. The critical crack depth for cracks whose length greatly exceeds their depth is given by the equation:

$$a_{cr} = 0.2\left[\frac{K_{1SCC}}{\sigma y}\right]^2,$$

where σy is the 0.2 per cent proof stress, and assuming that the applied stress $=\sigma y$.

In general, it is clear that maraging steels compare favourably with other high-strength steels, and offer relatively high K_{1scc} values over a wide range of strengths. It is also clear that maraging steels can withstand greater crack depth without crack propagation under a given static stress.

There is some uncertainty regarding the roles of active path corrosion and hydrogen embrittlement in relation to stress-corrosion cracking of maraging steels. However, it is known that they are susceptible to hydrogen embrittlement, but to a lesser extent than other high-strength steels. This can result in fracture under static load above certain values depending on the level of hydrogen absorbed during corrosion, pickling, plating, from lubricants, heat-treatment atmospheres or welding. The time to fracture decreases with increase of stress above the threshold value. Removal of absorbed hydrogen and recovery of properties can be achieved by baking treatments as shown in Figure 54. The maraging steels exhibit fast recovery characteristics and a bake of 24 hours at 150–300°C is usually sufficient to recover the full mechanical properties of the material.

Electroplating and surface coating for corrosion protection

Maraging steels can be electroplated with chromium, nickel or cadmium to provide suitable protection for use in severe environments or in highly critical parts where even slight corrosion would be unsatisfactory. Hydrogen which forms during cleaning and plating operations may be absorbed by the steels causing some embrittlement and baking for 24 hours at 200–320°C after plating is recommended to effect its removal.

Inorganic protective coatings of the various black oxide types used on conventional steels can be applied also to maraging steels. Both chromate and phosphate types have been successfully applied. Saturating the coating with oil enhances the protection afforded. Oxalate coatings of the types applied to stainless steels may also be of interest.

Organic coating systems which include polyurethanes and elastomeric neoprenes, such as are applied to conventional alloy steels, are being evaluated for nickel maraging steels.

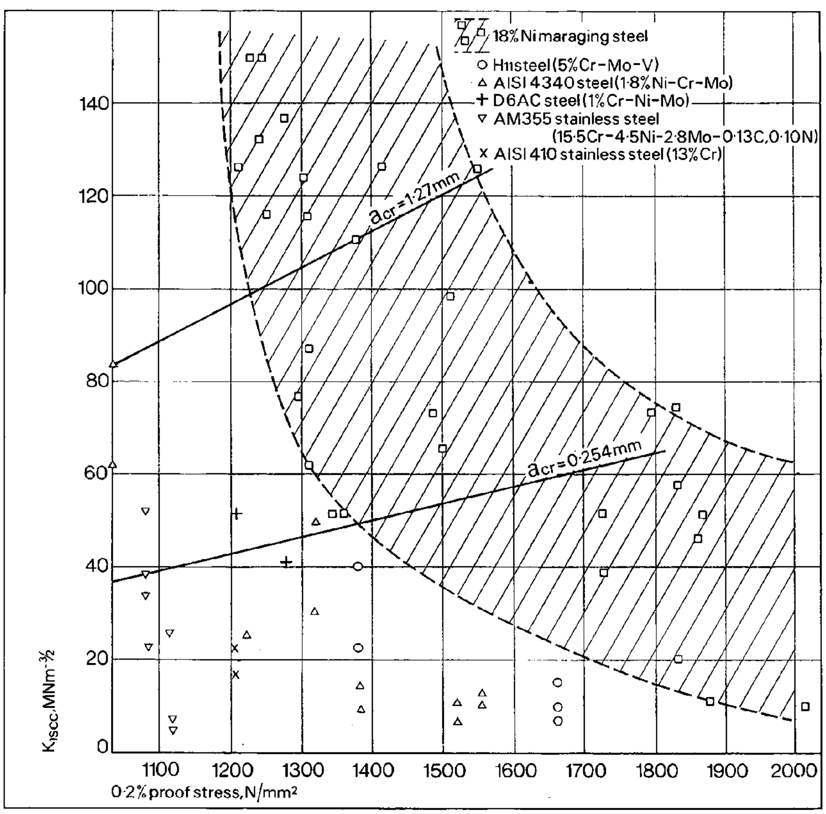

Figure 53. *K_{1scc} values of 18% nickel maraging steels and other high-strength steels as a function of 0.2% proof stress. Data from various tests in aqueous environments with and without sodium chloride.*

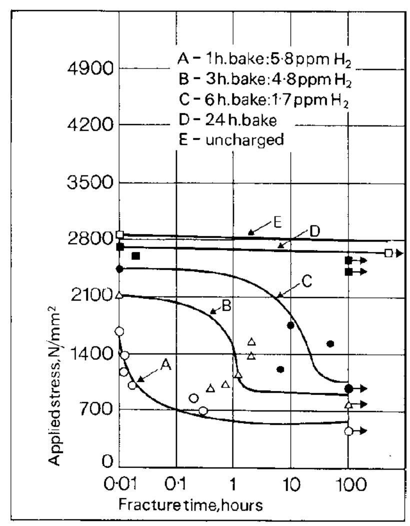

Figure 54. *Hydrogenated 18% nickel maraging steel regains static fatigue resistance rapidly when baked at 150°C. Tests were made on statically loaded notched tensile specimens hydrogenated by electrolytic charging at 0.011 amp/cm² for 21 hours.*